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The Pedology of Several Profiles Developed From the Calcareous Drift of Eastern Michigan

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THE PEDOLOGY OF SEVERAL PROFILES
DEVELOPED FROM THE CALCAREOUS DRIFT
OF EASTERN MICHIGAN

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EAST LANSING

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The Pedology of Several Profiles Developed from the Calcareous Drift of Eastern Michigan¹

By *ALLAN H. MICK*²

During the past fifty years a mass of information concerning Michigan soils has been collected and documented. A major portion of these records has been published as soil survey maps and reports, and in bulletins dealing chiefly with agronomy. Most of these early studies were, in fact, initiated and accomplished primarily for the purpose of answering practical questions. Systems of classification that have evolved in the course of this work are therefore inherently pragmatic in conception. Investigations fundamentally necessary to the evolution of a logical pedology have consequently suffered from a lack of emphasis. There is a need for additional geographic and physical and chemical quantitative data relating to soil genesis, morphology, and taxonomy.

This investigation was initiated to explore and perhaps to clarify several fundamental pedologic considerations that have so far escaped elaboration, particularly with respect to Michigan soils. It is an outgrowth of several seasons of field work in connection with the organized Soil Survey work carried on cooperatively by the Michigan Agricultural Experiment Station and the United States Department of Agriculture, in Midland, Newaygo, and Sanilac counties in the lower peninsula. The Gray-Brown Podzolic group of soils occurs here together with soil types which constitute a transition to the Podzol region of northern Michigan. A diversity of profiles are found here which are the results of soil-forming processes operating on and within heterogeneous glacial deposits. This investigation attempts to supply some conclusions concerning the nature of the calcareous till, particularly that found in the eastern part of the lower peninsula; to show what changes have evolved in it as a result of soil-forming processes; and to explain how these changes were brought about.

¹Taken from a thesis presented in partial fulfillment of the requirement for the Doctor's degree in Soil Science at Michigan State College.

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This study is especially concerned with changes in the subsurface. Consideration of the surface, or humus layer has been excluded from the following discussion chiefly for the following reason: all of the soils supported a similar deciduous forest cover. Therefore, differences exhibited by their respective solums are not caused to any large degree by variations in the nature of organic surface accumulations.

The findings and conclusions presented here are based on a theory that significant morphological differences in the profiles under study are exhibited by their respective A₂ and B horizons. The validity of the assumption is supported by accepted theories concerning the part played by eluviation, and particularly, illuviation in profile genesis.

REVIEW OF LITERATURE

The scope of this study embraces a considerable body of literature dealing not only with investigational techniques but also describing the history and nature of the specific area under consideration. As indicated by Fig. 1, this area includes four townships located in the southeastern part of Sanilac County in southern Michigan. Situated on the west shore of Lake Huron about midway down the Thumb, it is a region of especial interest to the glaciologist because of post-glacial lake fluctuations found here. The origin of the parent materials of the principal soils discussed herein and especially their manner of deposition have therefore been subjected to thorough study.

GLACIOLOGY AND PHYSIOGRAPHY

Leverett and Taylor have developed in intricate detail the glacial and post-glacial evolution of Michigan (37-41, 62). Briefly, the Pleistocene history is a story of a succession of climatic cycles and their resultant influence on land surfaces. Four times this region was overridden by continental ice-sheets. Local advances were in the form of a lobe which pushed generally southward down, and was more-or-less guided and confined by, the Huron valley. Minor westward pressures pushed the ice-sheet out over the confines of the Huron depression and onto the adjacent highland shelf. Cold cycles marked by glacial advances were followed by warm cycles when the ice front melted back; and during warm inter-glacial periods, generally longer in duration than glacial periods, newly formed land surfaces were weathered and eroded.

The surface drift and present landscape, on the whole constructive in character, are inherited from the fourth and final glaciation. As the

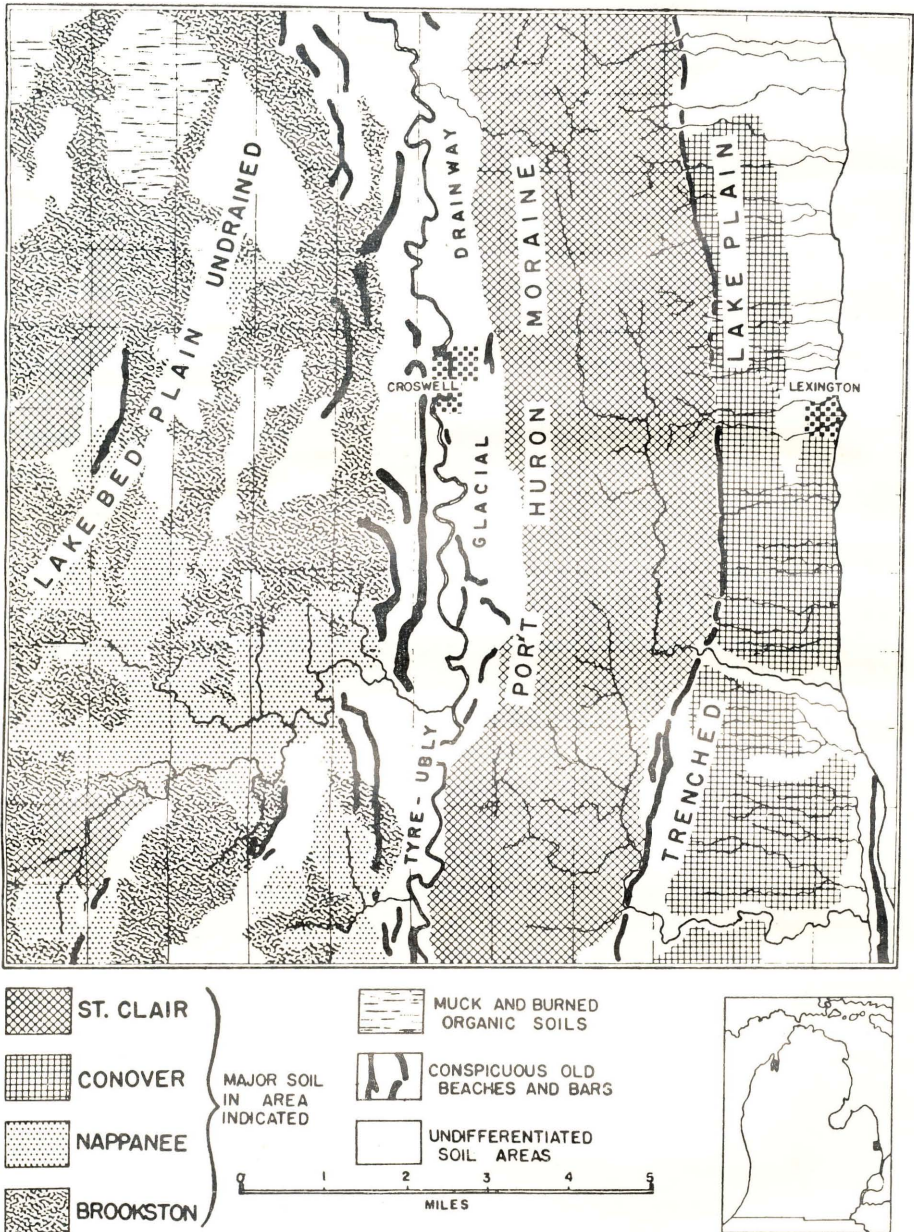


Fig. 1. Sketch map of the area studied, showing location, physical landscape features, and distribution of the four major profiles. Note that Nappanee areas are associated with tributary drainage into the Black River which now occupies the old Tyre-Ubly valley.

last ice sheet melted, the waters so formed were impounded along the glacier front in the form of lakes which persisted for long periods of time. The history of these lakes is now fairly well known, their various stages and basins having been deduced from many old beaches that are in some places conspicuous surface features.

According to Leverett and Taylor the western half of the area under consideration is a lake-bed plain formed when debris accumulated as the ice melted in lakes confined along the glacier front. The average elevation of this plain is some 150 feet above the present level of Lake Huron. In the southwest an area of greater elevation is marked by a slightly rolling surface which is thought to represent land-laid till. In the northern part of the lake-bed, a small portion of rolling, sandy moraine forms a minor elevation noted for its numerous boulder traces, which mark the position of a relatively short stop of the ice-front. Elongated, crescent-shaped beaches distributed systematically across this plain indicate successive stages of Lake Whittlesey as it subsided eastward into the Tyre-Ubly drainage channel, at one period a major outlet for glacial waters from the Saginaw ice lobe. This major valley, now occupied by the Black River, bounds the lake-bed on the east. It is in turn confined on the east by the strongly-developed linear Port Huron moraine. This pronounced feature marks the limits of a distinct readvance of the continental ice-front as distinguished from a mere halt in the course of its recession. It commands the plain on its west by some 30 or 40 feet, rising to a maximum elevation of over 760 feet above sea level or 180 feet above the present Lake Huron. The Port Huron moraine falls eastward on an average slope of 50 feet per mile to the wave-cut bluffs that border the lake beaches. A gently sloping plain thus formed is cut by minor border drainage valleys and by numerous streams that have trenched narrow, steep-sided channels. These small youthful valleys grow progressively deeper to become confluent with the lake at the foot of the bluff which is nearly vertical in a few places and rises to an average height of about 30 feet above the present water line. Old beach ridges representing successive stages of lake subsidence are conspicuous features superimposed on this trenched plain; the highest and most prominent of these is Warren Beach, nearly 140 feet above lake level.

The Port Huron moraine and the lake-bed plain on the east are underlaid by remnants of pre-Wisconsin drift which emerge in places near the bottom of the lake-shore bluff. Under the glacial drifts are

thinly-laminated blue shales of the Coldwater formation. On the west, these shales are overlaid by Marshall sandstone formations. Basement rock strata dip westward. Drift depositions do not conform to rock surfaces but vary in thickness, with no apparent relation to basement conformations, from about 20 to over 250 feet (24).

SOIL PROFILES

A detailed study of the soils in this area indicates that most profiles are similar to those already described in survey literature (8, 55). The four principal series on which this investigation is focused—the St. Clair, Conover, Nappanee, and Brookston—have been generally defined in terms of horizon characteristics and topography. So also have the incidental Isabella, Miami, and Bellefontaine that occasionally serve as reference profiles (49, 61, 64).

Miami, Conover, and Brookston profiles were first recognized on the calcareous drifts of Ohio and Indiana. Soon after their definition (1, 9, 18), they were also mapped in Michigan. Bellefontaine was also first defined in Ohio in 1912 (14), and shortly thereafter was brought to Michigan. Nappanee and Isabella were separated from the original Miami (63, 68), the former because of its heavy texture and imperfect drainage, the latter because of its red hue. Finally, in 1929, St. Clair series was separated from Miami (16) because it appeared somewhat lighter in hue, displayed a less conspicuous color profile, and occurred on what were thought to be water-laid rather than land-laid moraines; in addition, St. Clair was distinguished by a relatively high shale content in the parent material (3). Recent descriptions of these seven profiles as they are now defined are contained in survey reports for the Michigan counties of Lenawee (67), Newaygo (49), and Ingham (64).

There are also available data concerning the chemical and physical composition of Michigan soils developed from clayey tills. In 1923, McCool, Veatch and Spurway (43) published the results of detailed observations of 16 selected Michigan profiles; they concluded that their laboratory findings pointed to fairly consistent physical and chemical differences for the separate horizons as interpreted in the field. Analysis of 14 additional samples was subsequently completed (65) to confirm these early conclusions.

Marbut's descriptions of soils in this region (44) were based on data obtained chiefly from Ohio and Indiana in the Gray-Brown Podzolic region. The work of Harmer (26) in Minnesota is an early

example of the emphasis placed on complete chemical and physical studies. His conclusions concerning the essentially uniform chemical characteristics of local drifts have been confirmed by subsequent investigations (33, 50).

INVESTIGATIONAL TECHNIQUES

The literature on chemical and mechanical analytical methods is so well known that there is no necessity for a complete review. The chemical procedures used in this study are those summarized in the fourth edition of the Official Methods of the A.O.A.C. (57). Mechanical analyses were accomplished by means of the hydrometer method perfected by Bouyoucos (5, 6, 7, 69, 70).

In the field of mineralogy, many analytical procedures have already been perfected by sedimentary geologists (4) whose methods were adapted to the investigation at hand. A convenient starting point is the classification of sedimentary minerals into two groups on the basis of their specific gravities (2). The value 2.85 is generally arbitrarily accepted as the dividing point between the so-called "light" and "heavy" minerals. The light fraction, which includes quartz, calcite, feldspar, the clay minerals and micas, usually comprises about 98 percent of a sediment. The heavy fraction, which constitutes less than 2 percent of most samples, includes a much greater variety of mineral species and is therefore considered more useful in describing the characteristics of a sediment or soil material (28).

Much effort has been expended in an attempt to arrange soil minerals in order of their resistance to weathering (52). Zircon, tourmaline, quartz, rutile and apatite are considered relatively stable (52, 60, 50, 28, 47), although there is some evidence that even zircon (22), and certainly garnet (28) and apatite (50), are soluble under certain conditions.

A number of mineralogical investigations have been made of the heavy assemblages of glacial till (23, 34), most studies being directed towards the separation of the various drifts of the Pleistocene period and a comparison of sediments of different geologic ages (35, 66). A notable conclusion from Kruger's work (33) is that few mineral species are diagnostic of any one drift sheet. In other words, the same association of heavy minerals tends to dominate all Pleistocene drifts. Kruger concluded that a fairly certain identification of a particular drift can be obtained from a knowledge of its carbonate content and heavy mineral assemblage.

Heavy mineral studies of the soil solum, as distinguished from parent material, are not numerous. In Australia, residual surface soils were found to be related to parent rocks (11). Studies of glacial soils in England and Scotland have confirmed the Australian conclusions; it has also been deduced that local differences in silicate content of surface horizons are a reflection of variations in local parent rocks from which a majority of tills are known to be derived (27, 29).

In the United States, McCaughey and Fry (42) were petrographers who made special contributions to pedology. Studying sand and silt fractions of many samples from every part of the country, they discovered that epidote and hornblende are common in most soils. They concluded that any common rock mineral will be found in soil, a conclusion that suggests the possibility of nearly all surface soils being contaminated by windblown materials.

Jeffries and White were among the first in this country to delve into the mineralogy of soil profiles (30, 31). Their work revealed that in the eastern states soils developed from limestones, dolomites, and shales were all similar in their qualitative mineral content. They concluded that heavy mineral species vary more in proportion and total quantities than in number, and that a good comparison of different soils might be obtained by determining the relative percentages of only outstandingly common heavy minerals. Cady (10) compared heavy minerals from A and C horizons of several Podzol and Brown Podzolic forest soils to show that podzolization significantly reduces the amount of hornblende in solum horizons. Epidote, garnet, and magnetite appear to be little affected.

Mickelson (50) recently investigated the heavy mineral assemblages of three soils of the Miami catena. His results indicate that weathering processes contributing to the formation of Brookston and Miami profiles in Central Ohio are probably not similar. The most conspicuous difference in heavy mineral assemblages of these soils was in the presence of considerable apatite in all horizons of the Brookston profile; in the Miami, on the contrary, apatite was found only in relatively unweathered material. He also discusses the genesis and morphology of Miami, Bethel, and Brookston profiles as indicated by changes in their heavy mineral species in the various profile horizons. A significant trend is noted in this work, which shows the influence of Marshall and other later investigators. Mickelson treats his data on a volume rather than weight basis to reveal fallacies that were unap-

parent in previous comparisons. His conclusions depart in some measure from accepted concepts of soil genesis, especially in de-emphasizing the role of illuviation in the evolution of the still rather youthful profiles developing in glaciated regions.

The loessial soils of the mid-western states have received considerable attention in late years (2, 28). Pertinent findings are that color in loess is due to the type and quantity of clay minerals present (51), and that visual differences in loess and loessial soils are more closely associated with variations in carbonate content than with variations in texture (58).

Heavy mineral studies of Michigan soils have so far been limited to sandy materials. Johnsgard (32) discovered that a sandy ground-water podzol showed a marked depletion of hornblende, augite, and actinolite minerals, as well as feldspars, throughout the solum; on the contrary, a half-bog profile did not reflect this type of weathering. After studying seven widely separated sandy podzol profiles, Matelski (47) found no significant differences in heavy mineral assemblages over a wide area. A significant variation was discovered, however, in the relative quantities of heavy species present in fine sand fractions. In other words heavy mineral particle-size distributions were proved to be strikingly dissimilar and differed also, from horizon to horizon. Most resistant were garnets and opaque species; least resistant was hornblende. In these sandy profiles the B horizon organic material appeared to be an effective weathering agent with respect to hornblende. B horizons were therefore found to contain smaller quantities of unweathered heavy minerals than either the A or the C horizons.

The application of petrographic methods to soil studies has been summarized by Fry (20). Techniques of sampling and counting have been perfected by others (46, 12, 15, 21, 59, 45). A study of these investigations leads to the conclusion that the most practical approach is to study heavy minerals of a single size fraction (17, 25, 54) after treating with suitable reagents to insure that all interfering coatings have been removed (12, 45, 47). Probable errors involved in accomplishing the necessary microscopic counts have been analyzed by Dryden (19) and Rittenhouse (53) who furnish useful curves to show how many grains must be counted to yield a desired degree of accuracy.

This brief review of literature has disclosed an array of methods and techniques employed by numerous investigators in the past 25

years. The summarized studies have been directed towards a variety of objectives, and have dealt with different kinds of materials subjected to many kinds of weathering. With regard to pedology, the information so far obtained is only fragmentary, although it does shed considerable light on many aspects of soil genesis, morphology, and taxonomy.

This study in Michigan is an application of the available and recognized methods and techniques to several clay profiles. The selected profiles are of interest because they (or very similar profiles) are widely distributed in the lower peninsula, because they are typical of the productive and fertile soils of the state, and because they comprise a nearly complete drainage catena (8).

In the following pages, St. Clair, Nappanee, Conover, and Brookston profiles, on which the study is focused, are defined by brief descriptions together with comments necessary to a proper understanding of their relationships. There are also presented certain results obtained from an application of the afore-mentioned techniques and an analysis of pertinent data. Information concerning physical, chemical, and mineralogical characteristics of the four selected profiles and occasional reference profiles is discussed under separate headings. And finally, the findings of these convergent lines of investigation are brought together in the discussion of the St. Clair solum.

PROFILES INVESTIGATED

FIELD DESCRIPTIONS

Observations in the field reveal that the common profile on the clayey calcareous till in the rolling uplands comprising the Port Huron moraine has already been described and defined as St. Clair (3, 16, 55). Intimately associated with this zonal soil are small areas of Conover and Brookston developed in successively lower drainage positions, all being members of a single drainage catena. These three soils have developed from similar parent materials under different degrees of drainage, and therefore different kinds of weathering.

The Conover profile is most widely distributed on the trenched lake plain east of the moraine where it is associated with soils developed from a thin veneer of sand over icelaid till. Brookston and Nappanee are encountered on the flat, wet, lake-bed plain west of the Black River Valley. There is little doubt that the Brookston profile has developed in places which, within the memory of the present inhabi-

tants, were covered with surface water for a major portion of the year. Nappanee, intimately associated with Brookston, has developed on slight elevations very slightly above the general level of the plain.

According to early settlers, all of this land supported a dense deciduous forest cover although there was some differentiation as to species. Beech and sugar maple, with local admixtures of elm basswood and white oak, were dominant on the St. Clair soils. Brookston was characterized by elm, ash, silver maple, hickory and swamp white oak. Conover and Nappanee supported a mixture of these two cover types.

There are no apparent lithologic differences in the drift under these four series. Massive bluish-gray clay containing embedded fragments of shale, limestone, sandstone and a great variety of crystalline rocks in about the same proportions, appears throughout the whole area. Small fragments of brown, slightly weathered shale, of local origin, are common while limestone fragments constitute between 7 and 15 percent of their total bulk of coarse material.

ST. CLAIR SILT LOAM

A typical profile was found in an undisturbed woodlot in Worth Township, Sanilac County, 2 miles west and 3 miles south of Lexington.

Landscape—The St. Clair solum was confined to slopes and the crest of a low morainic ridge, slightly dissected by stream erosion. Mature trees at this location were sugar maple and beech with a scattering of basswood and white oak. Adjacent cultivated areas supported prosperous general farming enterprises.

Parent Material—This soil developed on late Wisconsin till exhibiting the "billowy" relief characteristic of morainic areas, except that adjacent slopes are stream cut, probably inherited from a minor glacial border drainage. The till is a calcareous clay composed of pre-glacial residuum of weathering and coarser fragments of many different kinds of igneous and sedimentary rocks, the latter mainly shale and limestone. At this particular site the carbonates have been leached out to a depth of about 30 inches.

Drainage—Surface drainage is accelerated by the gently sloping land surface. A compact B horizon and heavy texture of the underlying till might be supposed to impede drainage but these physical factors are offset by a great number of shrinkage cracks and joints which are

numerous in the upper B horizon and penetrate down a considerable depth into the parent till.

Soil Profile

| HORIZON | DESCRIPTION |
|-----------------|---|
| A ₀₀ | 0 to 1 inch loose, undecomposed forest litter and leaves. |
| A ₀ | 1 to 2 inches of well-decomposed leaf mold, neutral or mildly alkaline in reaction. A few light-colored sand grains are conspicuous. |
| A ₁ | 1 to 2 inches, dark brownish-gray granular mull containing a large proportion of organic matter that has been reworked and mixed by insects and worms. The lower portions are well-matted by fibrous roots. When exposed, this layer dries and becomes much lighter in color. Neutral or mildly alkaline in reaction. |
| A ₂ | 2 to 8 inches, light yellowish-gray silt loam. When dry this layer presents an ashy appearance, is friable, and exhibits a thin platy structure. Structural features are vague, however, and the layer is pierced by a myriad of small microscopic angular interstices and crevices. Slight pressure completely destroys this skeletal structure, leaving a mass of ashy, harsh sand and silt particles. A thin transition layer separating this horizon from that above is full of worm holes containing dark organic matter. Many large roots penetrate through this layer which is definitely acid in reaction. Feeder roots are not abundant. |
| A ₃ | 8 to 12 inches, light yellowish-brown, platy silt loam, slightly acid in reaction and penetrated by many large roots. Although major joints are horizontal, a few vertical shrinkage cracks originate in this layer. An imperceptible transition leads to the next layer. |
| B ₁ | 12 to 14 inches, light yellowish-brown silt loam exhibiting a fine angular fragmental or nutlike structure. In the lower part these fragments are 4 to 10 mm. in diameter and show color variations on those surfaces bounding major drainage cracks. Color variations apparently result from accumulations of dark brown colloidal coatings probably carried down from the layers above. Here the heterogeneity characteristic of B horizon structure first becomes apparent. Neutral reaction. |

- B₂ 14 to 27 inches, rather dark yellowish-brown clay loam or clay soil varying from neutral in the upper part to slightly alkaline in the lower depths. Well-formed angular fragments show little orientation except with respect to large crevices which, as relics of early developed joints induced by drying and consequent shrinkage, extend vertically through the horizon to penetrate the underlying unweathered material. Individual fragments exhibit heterogeneity in that their matrix appears relatively unweathered, being protected by one or more layers of fine materials accumulated on surfaces bounding major joint cracks. These surface coatings are dark brown and impart a dark color to the entire horizon when damp. Smooth surface cuts through the solum fail to reveal these color differences because of the relatively small bulk of the joint materials as compared with the exposed unweathered mass of the severed fragments. Large roots penetrating the horizons above terminate in this layer where numerous small roots grow in the cracks.
- B₃ 27 to 36 inches, another transition layer characterized by larger fragments than in the horizon above. In this layer the fragments are large and have an angular, blocky appearance. In the upper part the fragments are stained brown by colloidal coatings. In the lower part, white coatings, sometimes with a greenish tinge, appear. These seem to be secondary carbonates presumably leached down from the upper solum. In some places they are as much as 2 or 3 mm. in thickness. The interior of the structural blocks resembles the underlying relatively unweathered but oxidized till. Many small feeder roots cover the block surfaces.
- C₁ 36 inches and deeper. Light grayish-brown glacial till, clay loam in texture, containing a high proportion of limestone and dolomitic limestone fragments and rock powder. Many small fragments of igneous and sedimentary rocks are well-distributed through this till, together with large erratic stones and a few boulders. Brown shale fragments, possibly of local origin, are very common. This material is massive and compact, the upper portion severed by

vertical joint planes extending down from the layers above. Intersections of these vertical irregular joints impart to the till a massive columnar structure. Most major joint surfaces are well-coated with white or light colored secondary carbonates in which root traces have described delicate and intricate patterns. A few large roots extend into this material, generally following joint cracks and branching out into a myriad of fine rootlets confined to the cracks.

- C₂ 90 inches. An exposure along a steep stream-cut slope about 600 yards distant reveals unweathered till common to this series. Here the color is drab gray and uniform. No shrinkage cracks are observed and the whole mass seems to be hard and compact in structure.

CONOVER LOAM

The profile studied in this investigation was found in an undisturbed woodlot in Worth Township, Sanilac County, ½ mile west and 3 miles south of Lexington. This soil has been tentatively correlated as Conover in the partially completed survey of Sanilac County. It differs from many Conover profiles in Michigan in that it appears to be slightly more mature.

Landscape—A typical solum was found on flat and very gentle slopes of the trenched lake plain. Beech was the dominant tree species in this woodlot, although sugar maple and basswood were also common. Cultivated areas of Conover and the associated Allendale soils are used for general farming or dairy enterprises.

Parent Material—This soil is underlaid by late Wisconsin till which has the common lithologic character previously described. However, there is a thin surface veneer of coarse matter which has resulted from wave sorting. At this site the carbonates are leached to a depth of about 28 inches, which is 4 or 5 inches deeper than elsewhere.

Drainage—External drainage is fair but internal drainage is somewhat impeded as indicated by mottled colors above the compact B horizon. Temporary water-logging occurs during spring seasons but the upper solum becomes excessively dry during the summer drought periods.

Soil Profile

| HORIZON | DESCRIPTION |
|-----------------|--|
| A ₀₀ | 0 to 1 inch, loose, undecomposed forest litter and leaves. |
| A ₀ | 1 to 2 inches, well-decomposed leaf mold mildly alkaline in reaction. Shows evidence of much reworking by earthworms and insects. |
| A ₁ | 1 to 2 inches, very dark gray or brownish-gray granular and friable loam, slightly acid to neutral in reaction. |
| A ₂ | 2 to 5 inches, pale gray or yellowish-gray, very fine sandy loam, medium to strongly acid in reaction. This layer shows a moderately developed phylliform structure and contains few feeder rootlets. |
| A ₃ | 5 to 11 inches, light yellowish-gray plastic loam with conspicuous mottling of gray and yellowish-brown. Exhibits a phylliform structure and is strongly acid in reaction. |
| B ₁ | 11 to 12 inches. Similar to above layer but with incipient brown coatings on the surface of vertical joint cracks which begin to form and are very numerous in this layer. Here weakly phylliform compact material begins to take on a nuciform appearance, the fragments being small, well-formed, and sharply angular. |
| B ₂ | 12 to 20 inches, extremely tough and plastic clay loam, yellowish-brown mottled with gray in the upper part. When dry a nutlike structure is apparent, the surfaces of the fragments being dark brown while their interior is much lighter in color. |
| B ₃ | 22 to 24 inches, grayish and mottled brown friable calcareous loam till with a massive columnar structure resulting from the penetration of shrinkage cracks. |
| C | 24 inches and deeper, light grayish-mottled massive and compact till. |

NAPPANEE SILT LOAM

A typical profile was found in a pastured woodlot in Fremont Township, Sanilac County, 6 miles west and 4 miles south of Lexington. It differs from the Nappanee mapped in some other localities in Michigan in that it occurs on flatter landscapes.

Landscape—The typical profile was found on a slightly undulating plain where it occupied the rises or elevated portions, whereas Brookston formed in associated depressions. Nappanee areas are generally associated with natural drainage ways. Forest cover was dominated by a mixture of maple, beech, basswood, and elm. Cultivated areas are used for general farming and dairying.

Parent Material—This soil also developed in late Wisconsin glacial till which may have been deposited in water along the front of the moraine. In appearance it is similar to the parent material of St. Clair and Conover.

Drainage—External and internal drainage are slow. Temporary waterlogging in the spring necessitates careful management. In summer the surface is dry and droughty.

Soil Profile

| HORIZON | DESCRIPTION |
|-----------------|---|
| A ₀₀ | 4 to 1 inches, forest litter and leaves. |
| A ₀ | 1 to 0 inches, very dark gray, granular mull, well-worked by worms and insects. |
| A ₁ | 0 to 1 inches, dark gray, granular silt loam, breaking sharply into the layer below. Heavily matted by numerous fibrous rootlets. |
| A ₂ | 1 to 8 inches, pale gray friable loam exhibiting a vague phylloform structure. The top of this layer shows some worm holes filled with dark organic materials. The bottom is speckled with minute spots of red and yellow. Reaction is acid or slightly acid. |
| A ₃ | 8 to 11 inches, mottled silt loam, compact in structure and very acid in reaction. |
| B ₁ | 11 to 18 inches, heavy silty clay loam, mottled gray, yellowish-gray, and yellowish-brown in color. Plastic when wet, breaking into small angular fragments when dry. Compared with the foregoing profiles, the lack of major joint cracks and crevices is conspicuous. |
| B ₂ | 18 to 28 inches, plastic, mottled gray clay loam and silty clay loam. The variegated color is not the result of colloidal coatings on the surfaces of structural units, which here are inconspicuously developed. This is a massive layer relatively free of pebbles and small fragments. |

- B₃ 28 to 40 inches, brownish gray, silty clay loam exhibiting subdued mottling. Structure is massive with few shrinkage cracks evident. Reaction is slightly acid at the top and alkaline below.
- C 40 inches and more, calcareous, gritty, loam till, pale brownish gray showing rusty yellow mottling. Structure is massive and compact. Contains a great variety of stones and pebbles among which shale and limestone are conspicuous.

BROOKSTON SILT LOAM

A typical profile was found in a pastured woodlot in Fremont Township, Sanilac County, 3 miles west and 2½ miles south of Croswell. Here it is associated with both Nappanee and Conover Soils.

Landscape—In this area the Brookston occupies a broad expanse of undrained plain, the drier parts of which are used for pasture and special crops. Forest species are chiefly of ash and elm.

Parent Material—This soil also developed in the late Wisconsin till. The surface was probably subject to wave-washing as the temporary glacial lakes receded.

Drainage—Because of its topographic position, this area received runoff and seepage from the surrounding more elevated land surfaces. For long periods in the spring this soil is waterlogged. Poor surface drainage is a great obstacle to agricultural exploitation of this series. Because of its clayey nature its internal drainage is likewise seriously impeded.

Soil Profile

| HORIZON | DESCRIPTION |
|-----------------|---|
| A ₀₀ | ½ to 1 inch, forest litter and leaves which appear to decompose very slowly. |
| A ₀ | 1 to 2 inches, well-decomposed litter and plant tissues, containing some mineral materials probably carried up by worms and insects. Reaction is mildly alkaline. Structure is somewhat fibrous and mucky when wet but granular when dry. |
| A ₁ | 2 to 3 inches, very dark gray, granular silt loam. Neutral to slightly alkaline in reaction. |

- A₂ 2 to 8 inches, light gray, compact, very fine sandy loam, acid in reaction.
- A₃ 8 to 16 inches, brownish-gray, plastic loam, breaking into angular blocky fragments, acid in reaction.
- B₁ 16 to 20 inches, slightly mottled, brownish-gray silt loam with an acid reaction. Plastic and compact, breaking into angular blocks when dry.
- B₂ 20 to 34 inches, mottled, plastic silty clay loam, slightly acid to neutral in reaction.
- B₃ 34 to 44 inches, drab gray, slightly mottled, light, silty clay loam, neutral or slightly acid in reaction.
- C 44 inches and below, drab gray, somewhat mottled, clay loam till containing free lime. Coarse rock fragments, including grayish-brown shale.

In summary, the St. Clair, Conover, and Brookston series together form a drainage catena. Despite essentially similar parent material characteristics, field observations indicate sufficient solum dissimilarities to justify the differentiation of these three profiles. Nappanee is an anomaly in this scheme because St. Clair or Conover might normally be expected to develop where Nappanee has been mapped. Exhibiting some characteristics of an imperfectly drained soil, especially in its mottled subsoil colors, and also of the well-drained soil in that it has a conspicuous textural B horizon, Nappanee is not considered zonal in its development. Owing to its heavy-textured B horizon, Nappanee is perhaps best categorized as a planosol.

Rather than the differences, it was perhaps the many similarities noted to exist between these profiles that prompted a further, more detailed examination of their parent materials and solums. The remainder of this discussion is devoted to results obtained from several convergent methods of analysis and comparison.

PHYSICAL COMPARISONS

Characteristics often employed to describe soil and soil parent materials are those of mass and size. In order to determine uniformity, or lack of uniformity in the profiles in question, the volume weights, specific gravities, and particular size distributions of the A₂, B₂, and C horizons in each profile were measured. Details of sampling and laboratory techniques are recorded in Appendix I.

VOLUME WEIGHT AND POROSITY

Volume weights are important because they are used later for converting weight percentages into volume relationships. The values listed in Table 1 are therefore of interest since they constitute a basis for deductions presented hereafter.

Table 1 reveals that local variations in parent material densities are slight. On the other hand, differences in volume weight and specific gravity appear to have resulted from weathering. With the exception of the Brookston profile, volume weight differences between any two soils are less than differences between any two horizons of a single profile. Judging only from density changes, the Brookston series is the least weathered of the four. Changes in the density between the parent material and the weathered horizons of the other three soils are of a strikingly similar magnitude. An explanation of these roughly equal changes is most likely found in the fact that weathering has resulted chiefly in a loss of carbonates, a point that will later be amplified. Tables 5 and 6 show that the carbonate content of the three parent materials was about the same; it was not great enough, however, to constitute a continuous system within the matrix. Upon its removal, therefore, the structure did not collapse but merely developed a higher degree of porosity as the carbonate particles disappeared. Since the carbonate contents were similar, the increases in porosity in the various solums were similar. In this respect Napanee appears more closely related to the well-drained St. Clair than to the poorly-drained Brookston, a relationship that also prevails in other characteristics.

These data illustrate another point of interest in that porosity is shown to decrease with depth, reaching a minimum in the parent material. If the illuviated horizon truly contains accumulated materials translocated downward from the leached layers above, there must have occurred some concomitant volume expansion within the B horizon proper. Because there has been no increase in density of the illuviated horizon, but rather a decrease in density with respect to the parent material, then the weathering of this particular layer must have resulted in complementary increases over that volume originally occupied by the unweathered materials. This aspect of illuviation has seldom been mentioned by soil morphologists, perhaps because it is a discrepancy that cannot be fully explained by present theories concerning podzolization in till materials. There is a pos-

TABLE 1—Volume weight, specific gravity, and porosity of the selected profiles

| Profile..... | St. Clair | Conover | Nappanee | Brookston |
|-----------------------------------|--------------|---------|----------------|-----------|
| Drainage position..... | Well-drained | | Poorly-drained | |
| Parent material (C) | | | | |
| Volume weight* | 1.76 | 1.69 | 1.71 | 1.73 |
| Specific gravity** | 2.67 | 2.67 | 2.66 | 2.66 |
| Porosity*** | 34.1 | 36.6 | 35.6 | 34.9 |
| Eluviated zone (A ₂) | | | | |
| Volume weight* | 1.37 | 1.39 | 1.33 | 1.41 |
| Specific gravity** | 2.65 | 2.65 | 2.65 | 2.66 |
| Porosity*** | 48.3 | 47.5 | 49.8 | 46.9 |
| Illuviated zone (B ₂) | | | | |
| Volume weight* | 1.55 | 1.56 | 1.59 | 1.48 |
| Specific gravity** | 2.70 | 2.69 | 2.69 | 2.67 |
| Porosity*** | 42.6 | 42.0 | 40.9 | 44.6 |

*Average of duplicate measurements on duplicate samples.

**Average of duplicate measurements on a single sample.

***In percent by volume, calculated from the values above.

sibility, of course, that some expansion has occurred within the B layer although its structural characteristics lead to the deduction that contraction, rather than expansion, has been dominant.

This conclusion is even more apparent when it is understood that only stable structural units are represented by the volume weight and porosity values, that major interstices resulting from shrinkage of the structural units and other spaces such as worm holes and large root channels were excluded by careful sample selection. It is thus apparent that the low values characterizing any A₂ horizon actually represent degradation caused by a loss of material from within the structural unit proper. Application of this reasoning to the respective B horizons, reveals that they, too, must have been subjected either to leaching or to volume increases of considerable magnitude. Of these two alternatives the former appears most probable.

Another deduction is pertinent at this point. It concerns the development of the phylliform, platy, or laminated structure which characterizes eluviated horizons in many Gray-Brown Podzolic profiles, and which is particularly conspicuous in the St. Clair solum. Consider first a theoretical minimum volume weight that may be attained by soil materials. If all particles are spherical in shape, equal in size, and loosely packed, the minimum volume weight¹ value is 1.38 with a corresponding porosity of 47.7 per cent. Volume weights of the

¹Volume weight = $\frac{\text{Weight of unit diameter sphere, specific gravity 2.65}}{\text{Weight of unit cube with a specific gravity of 1.00}}$

horizons in question closely approximate this theoretical value. This close agreement indicates that these eluviated materials are approaching or have reached their minimum volume weights; if more material is lost through decay and leaching, the layer must consequently contract. Minimum values for these eluviated materials were probably reached at an early stage of weathering so that considerable contraction is thought to have already taken place as will later be shown. In response to gravitational forces, vertical contraction has predominated over horizontal. This action has shortened the inherited vertical interstices which were then further obliterated by sloughing and filling. Horizontal joints and cracks were not, however, as greatly affected and have tended to persist within the mass. These inherited characteristics are modified by the development of additional horizontally orientated interstices caused by an incomplete collapse of structural units. The resulting predominance of horizontal over vertical interstices is thus a possible explanation of the laminated structure of highly eluviated materials.

PARTICLE SIZE DISTRIBUTIONS

In order to extract very fine sand fractions for mineralogical studies, representative samples were analyzed mechanically producing the results shown in Table 2. These data reveal that the profiles in question developed in materials of strikingly similar particle size distributions. Although silt dominates the St. Clair profile to a less degree than the other three, all are either clay loams, or very nearly clay loams, in texture. Compared with the reference profiles, St. Clair appears to resemble Isabella rather than Miami as far as particle size attributes are concerned.

All profiles exhibit definite textural horizons. Eluviated zones (A_2) are relatively low in fine separates, particularly fine clay. At the other extreme are the so-called illuviated zones (B_2) which are all relatively high in fine clay. The parent material textures are intermediate between A_2 and B_2 , a relationship pointed out by many previous investigators. These and similar figures on many other soils have appeared to justify an assumption that the fine clays have been produced and dispersed as a result of soil-forming processes, and that they were then transported downward to precipitate or flocculate in a zone of accumulation. The reference Bellefontaine profile reflects the actual intensity of illuviation in this region. Here no fine clays were found

TABLE 2—Mechanical analysis of the selected and reference profiles expressed in percent of their oven-dry sample weights

| Horizon | Fine clay | Coarse clay | Fine silt | Coarse silt | Very fine sand | Fine sand | Medium sand | Coarse sand | Fine gravel |
|----------------------|-----------|-------------|-----------|-------------|----------------|-----------|-------------|-------------|-------------|
| | Percent | | | | | | | | |
| ST. CLAIR | | | | | | | | | |
| A ₂ | 8.1 | 9.0 | 13.4 | 39.8 | 16.5 | 7.1 | 3.1 | 1.0 | 0.5 |
| B ₂ | 31.1 | 8.8 | 10.8 | 23.8 | 10.1 | 8.2 | 3.3 | 2.1 | 1.4 |
| C..... | 19.7 | 10.4 | 11.5 | 26.2 | 8.4 | 11.4 | 5.6 | 4.4 | 1.7 |
| CONOVER | | | | | | | | | |
| A ₂ | 1.5 | 6.8 | 13.9 | 33.5 | 17.7 | 11.6 | 7.3 | 4.2 | 2.2 |
| B ₂ | 26.1 | 14.1 | 13.2 | 22.5 | 8.9 | 7.2 | 2.9 | 2.2 | 2.4 |
| C..... | 14.4 | 16.5 | 12.3 | 26.1 | 13.6 | 8.4 | 2.8 | 2.1 | 2.0 |
| NAPPANEE | | | | | | | | | |
| A ₂ | 0.0 | 8.3 | 10.2 | 18.0 | 21.3 | 24.5 | 7.3 | 5.1 | 4.3 |
| B ₂ | 28.1 | 9.1 | 18.3 | 5.9 | 6.1 | 2.9 | 6.1 | 0.5 | 0.0 |
| C..... | 11.2 | 15.8 | 17.5 | 30.3 | 11.1 | 6.3 | 4.2 | 2.1 | 1.1 |
| BROOKSTON | | | | | | | | | |
| A ₂ | 4.7 | 13.2 | 22.2 | 31.1 | 10.3 | 8.7 | 3.9 | 2.5 | 1.5 |
| B ₂ | 23.3 | 9.8 | 31.4 | 15.9 | 5.7 | 4.4 | 3.9 | 2.4 | 2.5 |
| C..... | 12.1 | 13.1 | 34.7 | 22.4 | 5.6 | 4.2 | 4.0 | 2.3 | 1.1 |
| MIAMI | | | | | | | | | |
| A ₂ | 16.6 | 14.0 | 21.2 | 31.9 | 6.9 | 5.1 | 2.9 | 1.0 | 0.9 |
| B ₂ | 38.3 | 11.2 | 14.1 | 18.5 | 6.3 | 5.3 | 3.0 | 1.9 | 1.1 |
| C..... | 27.1 | 9.8 | 19.8 | 21.5 | 7.1 | 6.6 | 3.7 | 2.1 | 1.3 |
| ISABELLA | | | | | | | | | |
| A ₂ | 14.1 | 12.4 | 14.3 | 38.4 | 9.9 | 6.3 | 1.9 | 1.3 | 1.1 |
| B ₂ | 44.5 | 13.3 | 9.4 | 12.8 | 6.7 | 7.7 | 1.1 | 1.9 | 0.7 |
| C..... | 25.3 | 11.8 | 12.5 | 19.8 | 10.0 | 10.7 | 5.9 | 2.8 | 0.5 |
| BELLEFONTAINE | | | | | | | | | |
| A ₂ | 0.0 | 1.8 | 1.2 | 6.6 | 4.7 | 41.8 | 31.8 | 7.3 | 3.3 |
| B ₂ | 4.1 | 5.6 | 5.4 | 7.7 | 7.0 | 19.3 | 35.1 | 9.3 | 6.2 |
| C..... | 0.0 | 3.9 | 4.9 | 5.4 | 8.0 | 28.9 | 34.0 | 8.4 | 6.1 |

Fine clay.....0.001 mm. and less
 Coarse clay.....0.001 to 0.002 mm.
 Fine silt.....0.002 to 0.01 mm.
 Coarse silt.....0.01 to 0.05 mm.
 Very fine sand.....0.05 to 0.10 mm.
 Fine sand.....0.10 to 0.25 mm.
 Medium sand.....0.25 to 0.50 mm.
 Coarse sand.....0.50 to 1.00 mm.
 Fine gravel.....1.00 to 2.00 mm.

in the parent material. The B₂ horizon accumulation therefore indicates the magnitude of net changes arising from clay formation and illuviation under favorable conditions of pore size distribution and drainage.

A peculiarity of this kind of data, expressed in terms of oven-dry sample weight percentages, is that it exaggerates textural differences between horizons because the value of one constituent cannot decrease without a complementary increase in the value of another. This mode of expression has therefore done much to foster fallacious conclusions. An example is readily apparent in Table 2 where it may be noted, by comparing fine clay percentages, that "losses" from A₂ horizons are equalled, and in some profiles exceeded, by apparent "gains" in B₂ horizons (with respect to parent materials). Comparisons of this kind have, in the past, undoubtedly encouraged the acceptance of translocation as a major soil formation factor and have tended to overemphasize the role it plays in illuviation.

A more valid comparison of data of this nature is obtained by expressing textural characteristics on a volume basis. Calculations can then be manipulated with respect to a more constant reference so that a clearer picture emerges. A summary of these mechanical analyses calculated to a volume basis is presented in Table 3 which integrates the volume weight values of Table 1 and the carbonate contents of the various horizons (also see Table 5). Here it is revealed that the chief effect of soil forming processes has been the loss of carbonates from the upper horizons.

Judging from the values listed in Column 4 of Table 3, soil formation has brought about only relatively small changes in mass per unit volume of materials other than carbonates. Assuming, for example, that the St. Clair A₂ layer developed from an equal volume of parent material similar to the present C horizon, the total loss of minerals other than carbonates is about 13 grams. Concurrently the B horizon has lost some 4 grams of carbonate-free materials, despite the fact that a considerable quantity of carbonates still remains. On the other extreme, the Brookston profile exhibits a "gain" of materials other than carbonates in the A₂ horizon. This "gain" probably resulted from changes in structure other than mere degradation. Compaction, for example, may have resulted in an increase in density of the original surface layer. Another explanation is the afore-mentioned vertical shrinkage accompanying, and resulting from, carbonate loss.

Conover and Nappanee exhibit "gains" in their respective B horizons. This is particularly true of the Nappanee series which is noted in the field for its dense compact "illuviated" zone. These figures suggest that true illuviation may have been more dominant in

TABLE 3—*Particle size distributions of the selected profiles, expressed in grams of carbonate-free separates per 100 cc. of sample volume*

| Horizon | 1 | 2 | 3 | 4 | 5 | 6 | 7 | | | | | | |
|----------------------|---|-----|------|-----|------|------|------|----------------|-------------------|---------------------------|------|------|------|
| | | | | | | | | Volume-weight* | X.CO ₂ | Carbonate-free material** | | | |
| | | | | | | | | | | Total*** | Clay | Silt | Sand |
| ST. CLAIR | | | | | | | | | | | | | |
| A ₂ | | 137 | 0.0 | 137 | 24.4 | 74.0 | 38.6 | | | | | | |
| B ₂ | | 155 | 8.5 | 146 | 60.5 | 48.6 | 36.8 | | | | | | |
| C..... | | 176 | 25.5 | 150 | 53.5 | 44.7 | 51.8 | | | | | | |
| CONOVER | | | | | | | | | | | | | |
| A ₂ | | 139 | 0.0 | 139 | 11.6 | 65.8 | 61.2 | | | | | | |
| B ₂ | | 156 | 11.2 | 145 | 57.6 | 51.1 | 36.8 | | | | | | |
| C..... | | 169 | 31.3 | 138 | 52.4 | 45.5 | 40.1 | | | | | | |
| NAPPANEE | | | | | | | | | | | | | |
| A ₂ | | 133 | 0.0 | 133 | 11.0 | 37.5 | 84.1 | | | | | | |
| B ₂ | | 159 | 3.3 | 156 | 58.2 | 72.9 | 25.5 | | | | | | |
| C..... | | 171 | 34.2 | 137 | 46.5 | 56.3 | 34.2 | | | | | | |
| BROOKSTON | | | | | | | | | | | | | |
| A ₂ | | 141 | 0.0 | 141 | 25.2 | 75.2 | 40.0 | | | | | | |
| B ₂ | | 148 | 16.6 | 132 | 43.6 | 62.3 | 26.1 | | | | | | |
| C..... | | 173 | 39.8 | 133 | 43.4 | 64.4 | 25.5 | | | | | | |

*Grams per 100 cc. calculated from the values in Table 1.

**These values will be found not to agree with similar values calculated from Table 2 because the particle size distribution of the carbonates does not resemble that of the sample as a whole.

***Difference between columns to the left, and sum of columns to the right, in grams per 100 cc.

Nappanee than in the other three profiles. There is a possibility, however, that this enrichment was not transported as clay but that fine material has formed in place, a theory that will later be amplified.

Whether the foregoing deductions are well-founded depend upon the validity of the basic premise which has already been stated—that unit volumes of parent material have produced unit volumes of solum. Later evidence will indicate that this premise is perhaps fallacious and that deductions based on an assumption that volumes have remained unchanged are of little more value than conclusions based on weight percentages.

Concerning changes of particle size classes within horizons, a point of initial importance is the small quantities of sand contained in the St. Clair A₂ layer. It appears that sand grains near the surface of this exposed soil have disintegrated as a result of soil-forming process-

es. Disintegration of coarse particles is also evident in the B horizon although to a lesser extent than in the more exposed surface layers. Complementing sand particle disintegration is an increase in the quantity of silt which is apparently an ultimate particle size in this material. It is logical to assume that the original silt may also have disintegrated to produce some clay even though the total amount in the A₂ horizon is less than in the parent material, due presumably to weathering of the inherited clay particles. Although the A₂ horizon shows a net difference of about 30 grams of clay per 100 cc. when compared with the C, the B₂ horizon has "gained" only 7 grams of clay. This figure is not insignificant, but is much smaller than has commonly been supposed from a comparison of weight values.

This same relationship is shown in the clay content of the different horizons in the Conover, Nappanee, and Brookston profiles. "Losses" of clay from A₂ horizons of the three relatively exposed profiles are of about the same magnitude. The "gain" exhibited by the B₂ over the C horizon in Nappanee, however, is twice that in the St. Clair and Conover. On the opposite extreme, the Brookston profile shows a relatively small but significant "loss" of clay from its A₂ horizon with no complementary gain in the B. It is therefore concluded that the heavy texture of the Brookston B₂ horizon is due only to an apparent gain of fine materials resulting from an actual loss of carbonates. This decrease in bases may also be reflected in structural changes within the B₂ horizon, which has retained its clay as compared with the A₂ horizon which is depleted in clay. Dispersion is hence not physically apparent in these surface layers as it is in the noncalcareous B₂ except as it may have contributed to translocation of fine particles.

A contrast of some magnitude is discovered between the well-drained profile and those which have developed in lower drainage positions when the quantities of coarse separates in their various horizons are compared. It is apparent that the St. Clair solum contains less sand per unit volume than does its parent material whereas the solums of the other three contain more sand than their respective parent materials. These differences are certainly of a significant magnitude and cannot be rationalized by "weathering" hypotheses. Some other explanation must be sought. The topographic position in which these poorly-drained profiles have developed, and the post-glacial history of the land surface on which they are encountered, suggest a theory

that may offer at least a partial explanation for these observed textural contrasts.

The basis for this theory is found in the hypothesis of glaciologists (37, 39, 49) who have postulated that the parent material in which the Nappanee profile, for example, has developed was deposited under water and that the till plain was a lake bottom for a considerable period of time. There is little evidence to show how deep these lakes were for the major portion of their existence, but it is within the realm of possibility that their basins were subjected to wave-action during certain stages in the lake subsidence. The thesis is advanced that this wave-action accomplished considerable sorting of surface materials before they were eventually exposed to weathering forces. Nappanee is confined to the higher parts of a plain where surfaces might logically be expected to suffer a maximum amount of wave reworking. Brookston occurs in depressions which served as settling basins during certain stages in the history of the land surface.

It is thought that wave-working may have accomplished two things. First, on relatively high surfaces now occupied by Nappanee, wave agitation was effective in removing a considerable portion of the original silt and clay. These fine materials were removed laterally which accounts for the apparent increase in sand in the A_2 horizon of this soil. Underlying materials, later to become the B_2 horizon, remained unchanged. A second result was sorting of these sands according to their specific gravities. When the till plain was finally exposed to post-glacial climates, Nappanee areas were hence already characterized by a textural profile. Moreover, in the lower depths of the sandy surface horizon, was a relatively high concentration of heavy minerals, some of which later decomposed in place to produce the relatively fine-textured B horizon that is characteristic of the present solum. The high clay content in the B layer of Nappanee does not, therefore, necessarily represent a greater degree of translocation of fine materials than has occurred in the St. Clair series which supposedly represents the most weathered and most mature profile in the region. This theory applied to the genesis of such an anomolous profile as Nappanee appears to reconcile its topographic situation with the extreme differences of texture exhibited within its solum. The theory possesses an added advantage in that it minimizes the role of percolating water which moves very slowly in the small capillary spaces of these heavy subsoils.

This thesis appears equally valid when applied to Conover and Brookston. Conover occupies a topographic position intermediate between St. Clair and Nappanee. Like Nappanee, Conover occurs on a lake-bed plain that might also have been subjected to wave-action. This plain is not flat and level, however, but slopes to the east. It is thought that, as the lake subsided, successive areas were subjected to a maximum of wave activity. Because of its sloping nature, the plain as a whole was not wave-washed in its entirety for a long period of time as compared with Nappanee areas. Thus, although there was a moderate sorting of materials and some concentration of sand in the surface layers, the action was not intensive. Moreover, as the Conover lake-bed slowly emerged, it was concurrently trenched by streams and hence became better drained. The profile of the Conover is more closely allied to St. Clair than to Nappanee.

As applied to the Brookston areas, some sorting of materials may be attributed to wave-action, but the evidence is not so marked as in the higher parts of the plain. More important was the lateral movement of fine materials from adjacent elevations. The admixture of these fine particles which settled in the depressions modified an inherited texture so that differences in the Brookston solum are not so conspicuous as in the higher areas. The greater density of the Brookston A₂ horizon over its C may have been caused by this addition of fine materials; it is, therefore, not degraded in the same sense as similar layers in the other three profiles.

In summary, mechanical analyses of the St. Clair, Nappanee, Conover, and Brookston profiles indicate they have developed in parent materials showing more similarities than dissimilarities. Clay dominates their parent materials. Disintegration has been a major process within their solums, while decomposition and physical sorting are evident in the low proportion of fine particles in their surface layers. Variations in parent materials and textural differences within two other analogous profiles in the Gray-Brown Podzolic region are indicated by the Miami and Isabella series. Bellefontaine is presented as an example of an extreme textural class of materials and to show the probable extent of clay formation and illuviation in this climatic zone.

CHEMICAL COMPARISONS

Even more difficult to perceive than textural differences, because such characteristics and relationships are not visible and can be ascer-

tained only by laborious and involved analysis, are the chemical characteristics of soils and soil materials. Early investigators tended to over-emphasize total chemical analyses, especially in expressing comparisons in terms of weight percentages with little or no regard to complementary physical attributes of the materials being studied. In many instances this practice resulted in misinterpreting data and formulating fallacious conclusions. Use of the word *illuviation* in the description of standard profiles of the Gray-Brown Podzolic group of soils is perhaps evidence of a misconception of soil genesis under this particular climate, a misconception that has been fostered by difficulties of analyzing data of this nature.

TOTAL CHEMICAL ANALYSES

Despite the fact that total chemical analyses are wanting in some respects, such studies are valuable in determining the uniformity, or lack of uniformity, exhibited by parent materials and profiles developed from them. The following data are especially interesting because of a notable lack of previous information concerning heavy tills in Michigan. Table 4 presents detailed analyses in terms of the most important and bulky constituents of the several series under discussion. All values are oven-dry organic-free weight percentages, a manner of expression that is considered of value primarily in comparing these figures with already published data, which have nearly all been organized in a similar form.

Inspection of these figures illustrates that the soil materials in question are remarkably similar in chemical constitution despite variations in color and texture. The most variable component with respect to any profile appears to be carbonates, although silica also shows considerable variation. Extremes of composition resulting from texture may be noted by comparing the Bellefontaine and Nappanee profiles. Extremes of color are exhibited by the Nappanee, Brookston, and Isabella profiles. Another point of interest is the apparently high iron and alumina contents in the B horizons of all but the St. Clair profile.

In order to present this information in a simplified form, values of duplicate samples have been averaged and summarized in Table 5 which more readily shows the foregoing relationships. Here it is seen that the principal difference exhibited by the horizons of the selected profiles is in their carbonate content. Compared with differences in carbonate levels, other chemical differences are comparatively small.

TABLE 4—Total chemical analyses of the selected and reference profiles, expressed as percent of oven-dry organic-free sample weights. Values are averages of duplicate determinations.

| Horizon | SiO ₂ | Fe ₂ O ₃ | Al ₂ O ₃ | CaO | MgO | IL* | CO ₂ |
|----------------------|------------------------|--------------------------------|--------------------------------|-------------------|-------------------|---------------------|---------------------|
| Percent | | | | | | | |
| ST. CLAIR | | | | | | | |
| A ₂ | 82.5 82.1 | 4.2 4.0 | 6.6 6.7 | 0.7 1.3 | 0.4 0.5 | 2.1 3.4 | — 0.3 |
| B ₂ | 74.1 73.4 | 4.6 4.8 | 7.4 6.4 | 5.8 4.5 | 3.5 4.0 | 3.1 4.2 | 2.5 2.8 |
| C..... | 67.4 68.9 | 5.1 4.6 | 10.5 7.4 | 6.1 6.6 | 2.0 2.2 | 7.6 7.9 | 6.9 7.1 |
| CONOVER | | | | | | | |
| A ₂ | 79.3 78.4 | 4.0 3.4 | 6.2 6.8 | 0.2 0.1 | 1.2 1.2 | 4.6 5.1 | — — |
| B ₂ | 72.3 71.2 | 6.3 5.9 | 7.3 6.7 | 2.0 3.5 | 3.3 3.2 | 4.9 5.1 | 3.7 3.1 |
| C..... | 65.7 67.6 | 5.1 5.0 | 8.5 6.0 | 6.3 6.1 | 3.8 3.9 | 9.2 9.1 | 8.8 8.5 |
| NAPPANEE | | | | | | | |
| A ₂ | 82.1 83.5 | 2.5 3.7 | 7.5 7.3 | 1.4 0.9 | 0.7 0.9 | 2.7 1.7 | — — |
| B ₂ | 72.3 69.2 | 6.2 6.7 | 11.5 11.8 | 1.5 1.8 | 1.8 2.7 | 1.9 2.1 | 0.6 0.9 |
| C..... | 63.9 64.6 | 3.9 4.0 | 6.8 7.3 | 7.1 6.7 | 4.4 3.4 | 11.3 10.2 | 9.8 9.0 |
| BROOKSTON | | | | | | | |
| A ₂ | 78.4 77.4 | 4.4 4.1 | 8.6 8.9 | 1.1 0.9 | 2.8 3.9 | 1.2 2.4 | — — |
| B ₂ | 66.4 67.5 | 4.3 4.1 | 10.2 11.4 | 2.8 2.8 | 4.1 4.5 | 7.5 7.9 | 5.2 5.4 |
| C..... | 57.7 59.9 | 4.7 3.5 | 9.2 10.3 | 8.8 7.9 | 5.5 4.4 | 11.9 11.6 | 11.7 10.5 |
| MIAMI | | | | | | | |
| A ₂ | 81.3 80.1 **84.1 | 4.9 4.7 2.0 | 10.0 9.3 7.7 | 0.7 0.9 0.8 | 0.5 0.6 0.4 | 0.4 0.9 2.5 | — — 0.8 |
| B ₂ | 69.5 69.3 **63.7 | 7.2 6.3 6.0 | 9.1 12.4 16.5 | 2.8 3.6 1.2 | 2.5 2.1 0.9 | 3.6 3.4 5.5 | 2.3 2.0 0.0 |
| C..... | 60.2 62.5 **51.2 | 5.1 5.2 4.8 | 9.8 11.2 13.3 | 7.9 6.1 7.9 | 3.9 3.2 4.5 | 10.8 9.1 13.7 | 10.3 8.1 10.6 |

Table 4—Continued

| Horizon | SiO ₂ | Fe ₂ O ₃ | Al ₂ O ₃ | CaO | MgO | IL* | CO ₂ |
|----------------------|------------------|--------------------------------|--------------------------------|-------------|------------|--------------|-----------------|
| <i>Percent</i> | | | | | | | |
| ISABELLA | | | | | | | |
| A ₂ | 87.0 **88.2 | 2.8 1.6 | 4.6 5.2 | 0.6 0.7 | 0.3 0.5 | — 1.6 | — 0.9 |
| B ₂ | 85.2 **72.3 | 5.5 4.2 | 5.2 11.3 | 0.7 1.6 | 0.4 1.7 | — 3.5 | — 1.3 |
| C..... | 62.7 **54.2 | 4.2 4.7 | 4.4 5.0 | 8.9 13.1 | 4.8 5.7 | — 15.7 | 12.2 14.8 |
| ONTONAGON | | | | | | | |
| C***..... | 61.1 65.4 | 4.7 4.5 | 5.1 4.1 | 7.5 9.1 | 5.8 4.6 | 13.2 11.6 | 12.3 12.0 |
| SELKIRK | | | | | | | |
| Q†..... | 62.4 63.4 | 5.3 5.1 | 6.2 6.6 | 5.9 5.5 | 6.4 5.6 | 11.5 11.3 | 10.7 10.3 |
| BELLEFONTAINE | | | | | | | |
| A ₂ | 87.3 | 3.2 | 5.6 | 0.1 | 0.5 | 0.3 | — |
| B ₂ | 79.2 | 9.2 | 4.9 | 0.7 | 0.7 | 3.2 | 1.1 |
| C..... | 77.3 | 3.1 | 8.0 | 4.3 | 1.0 | 5.3 | 4.4 |

*Ignition loss.

**Samples collected by J. O. Veatch and analyzed by O. B. Winter of the Michigan Agricultural Experiment Station.

***Samples collected by James Tyson and analyzed by D. G. Sherman.

†Samples collected by Cash Wonsler.

This table also reveals a probable incidental relationship between topographic position and the carbonate content of parent materials.

A summary of greater value is presented in Table 6, wherein these chemical analyses have been weighted according to the apparent specific gravities of their respective horizons, a comparison of more significance than conventional weight percentages when considering the genesis of a particular profile. It is here even more apparent that loss of bases from the solum has been a major result of soil-forming processes. Differences among the various parent materials are seen to be not so great as they appeared when expressed as weight percentages.

A notable point made clear by Table 6 is that the St. Clair profile exhibits no true zone of accumulation over and above its parent material inheritance. With respect to the C horizon, the B₂ horizon also

displays leaching, although not to the extent shown by the A₂ layer. The relatively heavy texture of this B₂ horizon must result, then, from an *apparent* increase in clay complementing a loss of carbonates. Changes in structure may have accompanied this decrease in polyvalent cations from the B₂ horizon. Consequent dispersion of its clays may have, in turn, contributed to the "heavy" field characteristics that distinguish this so-called illuviated zone. Table 3 has already demonstrated a concurrent decrease in size of all particles so that the quantity of fine clay in the B₂ horizon is increased. It would seem that the evidence so far indicates the bulk of this fine clay is formed in place rather than infiltrated downward from the overlying A₂ layer.

Nappanee and Conover profiles exhibit a slightly, and possibly significantly, greater amount of iron in their "illuviated" zones than in their respective C horizons. This is especially true of Nappanee which also displays a greater quantity of alumina in its B₂ horizon. Another characteristic of some interest is the high amount of silica in the A₂ horizon of this soil, in contrast to St. Clair and Conover, which are characterized by significantly less total SiO₂ in their surface layers.

TABLE 5—Chemical analyses summary of the selected profiles expressed as percent of their oven-dry organic-free sample weights

| Horizon | X.CO ₃ | SiO ₂ | Fe ₂ O ₃ | Al ₂ O ₃ |
|----------------------|-------------------|------------------|--------------------------------|--------------------------------|
| Percent | | | | |
| ST. CLAIR | | | | |
| A ₂ | — | 82.3 | 4.1 | 6.6 |
| B ₂ | 5.5 | 73.7 | 4.7 | 6.9 |
| C..... | 14.5 | 68.3 | 4.9 | 8.9 |
| CONOVER | | | | |
| A ₂ | — | 78.9 | 3.7 | 6.5 |
| B ₂ | 7.2 | 72.0 | 6.1 | 7.0 |
| C..... | 18.5 | 66.7 | 5.1 | 6.7 |
| NAPPANEE | | | | |
| A ₂ | — | 82.8 | 3.1 | 7.4 |
| B ₂ | 2.1 | 70.8 | 6.5 | 11.7 |
| C..... | 20.0 | 64.2 | 3.9 | 7.0 |
| BROOKSTON | | | | |
| A ₂ | — | 78.1 | 4.2 | 8.8 |
| B ₂ | 11.2 | 66.9 | 4.2 | 10.9 |
| C..... | 23.0 | 58.9 | 4.1 | 9.8 |

TABLE 6—*Chemical analyses of the selected profiles expressed as grams per 100 cc. of organic-free sample. Each item is an average of four measurements obtained from duplicate determinations on duplicate samples.*

| Horizon | Total Weight | X.CO ₃ | SiO ₂ | Fe ₂ O ₃ | Al ₂ O ₃ | Ratios | |
|----------------------|--------------|-------------------|------------------|--------------------------------|--------------------------------|--|---|
| | | | | | | $\frac{\text{SiO}_2}{\text{Fe}_2\text{O}_3}$ | $\frac{\text{Al}_2\text{O}_3}{\text{Fe}_2\text{O}_3}$ |
| Grams | | | | | | | |
| ST. CLAIR | | | | | | | |
| A ₂ | 137 | — | 112.9 | 5.6 | 9.0 | 20.1 | 1.61 |
| B ₂ | 155 | 8.5 | 114.2 | 7.3 | 10.7 | 15.6 | 1.46 |
| C..... | 176 | 25.5 | 120.1 | 8.6 | 15.7 | 14.1 | 1.83 |
| CONOVER | | | | | | | |
| A ₂ | 139 | — | 109.5 | 5.2 | 9.1 | 21.1 | 1.75 |
| B ₂ | 156 | 11.2 | 112.5 | 9.5 | 10.9 | 11.2 | 1.15 |
| C..... | 169 | 31.3 | 114.2 | 8.6 | 11.4 | 13.3 | 1.33 |
| NAPPANEE | | | | | | | |
| A ₂ | 133 | — | 111.1 | 4.1 | 9.8 | 22.3 | 2.23 |
| B ₂ | 159 | 3.3 | 113.6 | 10.3 | 18.6 | 15.6 | 2.08 |
| C..... | 171 | 34.2 | 108.8 | 6.7 | 12.0 | 16.4 | 1.79 |
| BROOKSTON | | | | | | | |
| A ₂ | 141 | — | 110.3 | 5.9 | 12.8 | 18.7 | 2.17 |
| B ₂ | 148 | 16.6 | 99.2 | 6.2 | 16.2 | 16.0 | 2.65 |
| C..... | 173 | 39.8 | 101.5 | 7.1 | 16.9 | 14.3 | 2.38 |

In this regard the Brookston profile is also of interest since it, too, shows significantly higher amounts of silica in its A₂. These differences are summarized in Table 7.

Here it is seen that horizon development in the various soils appears to bear some relationship to the topographic position in which the respective profiles have developed. Thus the more exposed till, represented by St. Clair, is marked by great losses, or by the effects of more vigorous and intensive leaching. It is also seen that Nappanee, Conover, and Brookston, representing lower positions in the same drainage catena, are characterized by losses of a much smaller magnitude. Nappanee is unique in that its B horizon is characterized by larger quantities of SiO₂, Fe₂O₃, and Al₂O₃ than is its C horizon. The decreasing magnitude of these horizon differences, particularly differences in iron and aluminum, offers some foundation for concluding that profiles are formed as a result of leaching. The high amounts of silica in the A₂ horizons of Nappanee and Brookston cannot, however, be explained on the basis of leaching. A better explanation is found in the thesis

TABLE 7—Horizontal differences in chemical constituents of the selected profiles, expressed in grams per 100 cc.

| Horizon | SiO ₂ | Fe ₂ O ₃ | Al ₂ O ₃ |
|------------------------|------------------|--------------------------------|--------------------------------|
| <i>Grams</i> | | | |
| ST. CLAIR | | | |
| A ₂ —C..... | -7.2 | -3.0 | -6.7 |
| B ₂ —C..... | -5.9 | -1.3 | -5.0 |
| CONOVER | | | |
| A ₂ —C..... | -4.7 | -3.4 | -2.3 |
| B ₂ —C..... | -1.9 | +0.9 | -0.5 |
| NAPPANEE | | | |
| A ₁ —C..... | +1.2 | -2.6 | -2.2 |
| B ₂ —C..... | +3.8 | +3.6 | +6.6 |
| BROOKSTON | | | |
| A ₂ —C..... | +8.8 | -1.2 | -4.1 |
| B ₂ —C..... | -2.3 | -0.9 | -0.7 |

The + sign indicates that the horizon contains more than the parent material; - indicates that the horizon has less than the parent material.

offered in an earlier section which is not refuted by this new evidence but rather is strengthened.

The concept has been advanced that the surface layers of Nappanee were depleted in clay by the sorting action of wave-induced turbulence in the shallow waters once covering the area. It has also been suggested that the sandy residues may have been gravimetrically separated so that certain heavy clay-forming minerals concentrated in an enriched zone at some depth below the surface of the lake bottom sediments. This gravimetric sorting would simultaneously result in a chemical separation of the coarse sediments. Silica and certain potash-soda feldspars of a low specific gravity would remain on the surface while the heavier hornblende and plagioclase feldspars would sift downward, contributing to an enrichment of a zone below the surface. Subsequent weathering could be expected to produce relatively small quantities of clay in the upper silicious layers, while the enriched zone would produce relatively large quantities. This concept thus accounts for both the high silica content of the Nappanee surface and the relatively heavy texture of its B₂ horizon. A profile so formed would present striking texture contrasts and yet represent a minimum of clay

translocation (that is, illuviation). This theory thus brings together observable field characteristics of this particular solum.

Brookston materials represent depression sediments associated with wave-washed Nappanee materials. Pursuing the proposed thesis to its logical conclusion it is necessary to assume that the surface layers of Brookston were somewhat enriched by clays separated and laterally transported from the higher surrounding areas. This action is thought to be reflected in the relatively high iron and aluminum content of the Brookston solum. Brookston surface horizons also exhibit a relatively high silica content, which is explained on the basis of wave-action and consequent physical sorting of surface materials.

The relatively large losses of silica are of interest in considering the chemical weathering that has been accomplished in this particular climate. A study of meteoric waters throws additional light on this subject (Table 8) since it shows that their silica content is much higher than either their iron or alumina content. Moreover, Tables 7 and 8 reveal that subsurface drainage waters carry alumina and iron in about the same ratio as they are leached from soil. The silica-sesquioxide ratio of losses from surface horizons is, however, smaller than a similar ratio for meteoric waters, the former being somewhat less than unity while the latter is in every sample greater than unity. A possible, though perhaps hasty, conclusion is that iron and alumina must be deposited somewhere within the sub-strata, somewhere other than in the so-called illuviated zone of the solum. Additional evidence will later assist in clarifying this point.

To summarize, the results of chemical analyses appear to support the conclusion deduced from studying particle size distributions: that soil forming processes have resulted chiefly in removing carbonates

TABLE 8—Analysis of meteoric waters from eastern Michigan (48), expressed in parts per million

| Location | Source | SiO ₂ ppm. | Fe ₂ O ₃ ppm. | Al ₂ O ₃ ppm. |
|-------------------|--------|--------------------------|--|--|
| Armada..... | Well | 16.4 | nd | nd |
| Almont..... | Well | 16.8 | 2.4 | 4.0 |
| Bad Axe..... | Well | 11.2 | 1.0 | 2.2 |
| Brown City..... | Well | 11.2 | nd | nd |
| Harbor Beach..... | Lake | 10.0 | 0.0 | tr |
| Imlay City..... | Well | 12.0 | 1.8 | 3.8 |
| Marlette..... | Well | 8.8 | nd | nd |
| Memphis..... | Well | 19.2 | 0.7 | 3.2 |
| Port Austin..... | Well | 7.6 | 0.4 | 1.1 |
| Sandusky..... | Well | 8.0 | nd | tr |
| Uby..... | Well | 20.8 | tr | tr |

nd indicates no determination; tr indicates trace.

from the solum. Silica, iron and alumina have also been lost and these losses are generally apparent not only in the leached zone but also in the so-called accumulation zone. An exception to this generality is encountered in the anomalous Nappanee profile; it is argued, however, that these exceptional gains originated before this particular profile was exposed to soil forming forces and therefore do not invalidate the concept that disintegration, decomposition and leaching have dominated the genesis of the St. Clair-Nappanee-Conover-Brookston catena.

MINERALOGICAL ANALYSIS

It has already been shown that certain advantages are derived from expressing analytical values in terms of volume rather than weight. An application of this principle has revealed information concerning the relative importance of certain soil-forming processes in the evolution of Gray-Brown Podzolic profiles. Some idea has also been gained concerning the morphology of several selected profiles and their categorization in the pedologic taxonomy of a rather limited geographical area. Thus far, however, the argument is perhaps as misleading as earlier accounts of genesis and morphology; the fallacy here is in the assumption that present volumes are satisfactory reference criteria, despite the fact that there has already been an occasion to note that the present A₂ horizon probably is much thinner than the layer of parent material from which it evolved. An independent reference for judging volume changes, therefore, is an obvious requirement.

Pedologists seized the various petrographic techniques as they were perfected by sedimentary geologists and used them to describe soils and soil materials. The early work, however, consisted of little more than cataloging the various mineral species encountered. Not until the past decade has there been any serious attempt to correlate petrographic data with soil genesis. These efforts have been pioneered by Jeffries and Marshall and it is the latter who has suggested that resistant mineral species may afford the necessary and vital reference for indicating changes involved in profile genesis. It already has been seen that weight and volume references have not supplied a satisfactory index of the various losses and possible gains which evolved the profiles described herein. An attempt now is made to rationalize certain petrographic data with respect to the theory already set forth, in order to discover what new light this approach may shed on the older concept of illuviation as a major soil-forming force. In Table 9 are

summarized the findings of a petrographic investigation into the nature of the very fine sand fractions of the selected profiles.

It is of interest to note the similarity of the mineral assemblages here listed to those encountered by Kruger (33) in the late Wisconsin till of Minnesota, by White (66) in the Wisconsin drift of northern Ohio, and by Mickelson (50) in the Wisconsin drift of central Ohio. Quartz, calcite, feldspars, and hornblende appear to dominate most till assemblages reported by the above authors. In eastern Michigan drifts these four minerals constitute 50-51, 9-16, 12-20, and about 2 percent, respectively, of very fine sand fractions. The remaining very fine sand is dominated by rather amorphous appearing aggregates seemingly limonitic in character.

Heavy fractions of very fine sands, which are present in rather uniform quantities, are dominated by hornblende, a relationship that appears to be widespread according to the above-mentioned authors. Johnsgard (32) and Matelski (47) found that hornblende constituted the greatest portion of heavy mineral fractions of several Michigan sandy profiles. Besides hornblende, other important heavy minerals are garnet, epidote, augite, and several opaque minerals of which magnetite is the most abundant. In nearly all samples certain accessory species were also noted, the most numerous being titanite, rutile, ilmenite, leucoxene, biotite, pyrite, monazite, kyanite and chlorite. These accessory minerals are present in such small quantities, however, that no attempt was made to secure quantitative measurements since major morphological differences are found in the dominant species.

When one considers the profiles listed in Table 9, a marked similarity is found in quantities of various minerals present in very fine sand of the several soils. Here as in total chemical analyses, major differences seem to arise from the varying amounts of calcite present in parent materials, and in the apparent increases in resistant minerals in surface layers resulting from losses of calcite as a consequence of weathering. It should be borne in mind that all values listed in Table 9 are count percentages and that they therefore represent volume changes rather than weight changes.

Since these data, as well as chemical analyses, indicate that horizon dissimilarities are chiefly caused by differences in carbonates, a more valid comparison of profiles is obtained by recalculating all values to a calcite-free basis. Such a comparison is shown in the upper part of Table 10. Here it is seen that the quartz content in the very fine sand

TABLE 9—Petrographic analysis of very fine sands from the selected profiles, expressed as percent of the total particles counted

| Mineral | St. Clair | | | Conover | | | Nappanee | | | Brookston | | |
|-----------------|----------------|----------------|------|----------------|----------------|------|----------------|----------------|------|----------------|----------------|------|
| | A ₂ | B ₂ | C | A ₂ | B ₂ | C | A ₂ | B ₂ | C | A ₂ | B ₂ | C |
| Light fraction* | | | | | | | | | | | | |
| Calcite** | 0.0 | 3.1 | 16.1 | 0.0 | 0.1 | 9.7 | 0.2 | 1.7 | 10.9 | 0.0 | 3.7 | 12.9 |
| Orthoclase | 6.5 | 5.9 | 7.4 | 9.9 | 8.6 | 9.7 | 6.4 | 6.4 | 6.7 | 9.6 | 7.6 | 6.5 |
| Plagioclase | 11.6 | 14.9 | 13.5 | 11.0 | 13.5 | 9.3 | 12.4 | 20.6 | 11.8 | 9.7 | 9.5 | 5.9 |
| Iron oxides | 0.5 | 2.3 | 3.5 | 0.2 | 1.2 | 5.6 | 0.9 | 3.1 | 9.2 | 1.3 | 5.1 | 10.3 |
| Aggregates | 9.0 | 8.1 | 3.6 | 11.6 | 16.9 | 8.1 | 3.9 | 5.3 | 7.5 | 3.4 | 17.4 | 10.3 |
| Quartz | 69.6 | 60.7 | 52.4 | 64.7 | 55.5 | 51.5 | 71.4 | 57.4 | 50.3 | 74.9 | 53.9 | 51.2 |
| Percent*** | 97.2 | 95.0 | 96.5 | 97.4 | 95.8 | 94.9 | 95.2 | 94.5 | 96.4 | 98.9 | 97.7 | 97.1 |
| Number counted | 384 | 516 | 621 | 1101 | 978 | 742 | 586 | 721 | 513 | 837 | 621 | 541 |
| Heavy fraction* | | | | | | | | | | | | |
| Total† | 4.15 | 4.83 | 4.28 | 3.71 | 4.92 | 4.10 | 3.62 | 6.83 | 3.33 | 4.22 | 4.70 | 3.96 |
| Apatite | 0.5 | 0.2 | 1.8 | 0.0 | 0.5 | 3.8 | 0.4 | 0.7 | 3.4 | 3.1 | 3.7 | 2.6 |
| Augite | 4.8 | 6.1 | 10.0 | 5.5 | 7.2 | 8.1 | 7.4 | 7.0 | 9.3 | 7.3 | 7.2 | 8.9 |
| Epidote | 6.4 | 6.3 | 8.2 | 6.7 | 4.6 | 4.9 | 7.6 | 11.0 | 5.3 | 3.9 | 4.5 | 5.8 |
| Garnet | 9.6 | 10.3 | 10.9 | 10.2 | 13.1 | 13.2 | 11.0 | 9.4 | 7.5 | 9.1 | 9.0 | 8.1 |
| Hornblende | 49.5 | 49.3 | 49.1 | 50.0 | 51.2 | 45.4 | 48.3 | 47.6 | 50.1 | 52.6 | 54.2 | 48.8 |
| Opaque | 19.3 | 15.8 | 16.2 | 20.4 | 16.4 | 18.1 | 16.2 | 18.3 | 19.8 | 13.4 | 13.5 | 18.5 |
| Tourmaline | 0.7 | 0.6 | 0.5 | 0.6 | 0.5 | 0.4 | 0.5 | 0.4 | 0.4 | 0.6 | 0.4 | 0.3 |
| Zircon | 3.0 | 2.5 | 2.1 | 2.3 | 2.4 | 1.8 | 2.4 | 2.8 | 2.4 | 3.8 | 2.9 | 3.1 |
| Percent†† | 93.8 | 91.1 | 96.2 | 95.7 | 95.9 | 95.7 | 93.8 | 97.2 | 97.5 | 93.8 | 95.4 | 96.1 |
| Number counted | 543 | 691 | 571 | 783 | 746 | 831 | 817 | 971 | 1108 | 748 | 926 | 511 |

*Specific gravity of 2.90 was selected as the demarcation point between light and heavy species.

**The calcite group contains both calcite and dolomite.

***Sum of light minerals listed as compared to total light fraction, expressed in percent.

†Percent of very fine sand composed of heavy minerals.

††Sum of heavy minerals listed as compared to total heavy fraction, expressed as percent of particles counted.

fraction is relatively resistant, being present in greater quantities in surface layers than in the respective B₂ or C horizons. This difference is in part only apparent, because there has been some weathering of the feldspar minerals in the A₂ and B₂ horizons. On the other hand, total chemical analyses already have indicated that there has been considerable loss of silica, from the surface layers, perhaps more than was realized through the decomposition of silicate minerals other than quartz. Although very fine quartz could not be expected to contribute measurable quantities to these losses, nevertheless the tendency is towards decreasing, rather than increasing, quantities of total silica in the A₂ horizon.

In view of insignificant losses of materials other than calcite from the surface layers, it appears that the great differences in the quartz content of A₂ and B₂ horizons of the Conover, Nappanee, and Brookston profiles can be accounted for only by advancing an hypotheses of a non-conformity developed as a result of purely physical soil-forming processes. Additional evidence in favor of this theory is seen in the total quantities of heavy minerals in the very fine sand fractions of the various horizons of the selected profiles (see Table 9): while St. Clair displays a slightly greater quantity of heavy minerals in its B horizon, the other profiles, and especially the Nappanee, show differences of a much higher order. In fact, the large quantity of heavy minerals found in the B₂ horizon of Nappanee (as compared with the A₂ and C horizons of the same profile) cannot be reconciled to the probable intensity of weathering that has prevailed in materials situated in this particular drainage position.

Marshall (45) has recently advanced a petrographic theory for use in studies of soil genesis, a theory based on an assumption that certain resistant minerals remain relatively unchanged during profile development. Two or more resistant minerals found in the various separates are used as indicators of depositional or geological differences in parent materials. If the material were vertically uniform when weathering started, the ratio between any two of these mineral species should be constant throughout the profile. Pronounced variations in this ratio indicate depositional differences within the original parent material (50).

Zircon and tourmaline are generally accepted as suitable species for a valid application of this test. This selection unfortunately is of limited value in studying the data at hand because of the small num-

TABLE 10—Analysis of the mineralogical data listed in Table 9

| Minerals and ratios | St. Clair | | | Conover | | | Nappanee | | | Brookston | | |
|------------------------|---|----------------|------|----------------|----------------|------|--------------------|----------------|------|----------------|----------------|------|
| | A ₂ | B ₂ | C | A ₂ | B ₂ | C | A ₂ | B ₂ | C | A ₂ | B ₂ | C |
| | Percent of particles counted, corrected to a calcite-free basis | | | | | | | | | | | |
| Light fraction | | | | | | | | | | | | |
| Orthoclase..... | 6.5 | 6.1 | 8.8 | 9.9 | 8.6 | 10.8 | 6.4 | 6.5 | 7.5 | 9.6 | 8.2 | 7.5 |
| Plagioclase..... | 11.6 | 15.4 | 16.1 | 11.0 | 13.5 | 10.3 | 12.4 | 21.0 | 13.3 | 9.7 | 9.8 | 6.8 |
| Aggregates..... | 9.0 | 8.4 | 4.3 | 11.6 | 16.9 | 9.0 | 3.9 | 5.4 | 8.4 | 3.4 | 18.1 | 11.8 |
| Quartz..... | 69.6 | 62.8 | 62.5 | 64.7 | 55.5 | 57.1 | 71.4 | 58.4 | 56.5 | 74.9 | 56.1 | 57.6 |
| Heavy fraction | | | | | | | | | | | | |
| Auclite..... | 4.8 | 6.2 | 11.9 | 5.5 | 7.3 | 9.0 | 7.4 | 7.1 | 10.5 | 7.3 | 7.5 | 10.2 |
| Epidote..... | 6.4 | 6.4 | 9.3 | 6.7 | 4.6 | 5.4 | 7.6 | 11.6 | 5.9 | 3.9 | 4.7 | 6.7 |
| Garnet..... | 9.0 | 10.5 | 12.3 | 10.2 | 13.1 | 14.6 | 11.0 | 9.6 | 8.3 | 9.1 | 9.3 | 9.3 |
| Hornblende..... | 49.2 | 50.4 | 58.6 | 48.3 | 48.5 | 55.6 | 50.0 | 51.2 | 50.4 | 52.6 | 56.3 | 56.2 |
| Tourmaline..... | 0.7 | 0.6 | 0.6 | 0.6 | 0.5 | 0.4 | 0.5 | 0.4 | 0.5 | 0.6 | 0.4 | 0.3 |
| Zircon..... | 3.0 | 2.6 | 2.3 | 3.8 | 2.4 | 3.0 | 2.4 | 2.8 | 2.7 | 3.8 | 3.0 | 3.3 |
| | | | | | | | Weathering indices | | | | | |
| Zircon..... | 4.3 | 4.2 | 4.2 | 3.8 | 4.8 | 4.5 | 4.8 | 7.0 | 6.0 | 6.3 | 7.2 | 10.3 |
| Tourmaline Opaque..... | 6.4 | 6.3 | 6.5 | 8.9 | 6.9 | 10.0 | 6.8 | 6.5 | 8.3 | 3.5 | 4.6 | 6.0 |
| Zircon Garnet..... | 3.2 | 4.1 | 5.2 | 4.4 | 5.4 | 7.3 | 3.3 | 3.3 | 4.8 | 2.4 | 3.1 | 2.7 |
| Zircon Quartz..... | 53.8 | 47.8 | 56.3 | 72.2 | 62.4 | 66.7 | 79.2 | 30.2 | 60.1 | 44.9 | 37.8 | 40.1 |
| Zircon..... | | | | | | | | | | | | |

ber of particles counted in each sample, and because only a few zircon and tourmaline particles were found therein. Moreover, only one size fraction was studied, which presents a serious obstacle in the logical interpretation of mineralogical data, as Matelski (47) has recently shown. Notwithstanding these objections, however, an application of Marshall's theory is considered justified, providing its limitations are fully understood. In Table 10 certain ratios therefore are presented which are of interest in view of the findings of other investigators.

A useful point of departure in the problem at hand is found in the recent works of Cady (10) and Chandler (13) dealing with the resistance of the more important soil minerals to podzolic weathering. Their studies show that among the most resistant minerals are magnetite, quartz, garnet, and zircon. Moderately resistant minerals are epidote, orthoclase, and diopside. Easily weathered minerals are hypersthene, hornblende, plagioclase, and olivine.

If these conclusions are accepted, then the ratios listed in Table 10 indicate that of the four profiles, only St. Clair has developed in materials that were vertically uniform when first exposed to chemical weathering forces. The corresponding ratios for the various horizons of the Nappanee, Conover, and Brookston profiles vary so greatly that, despite the inherently great experimental error in these determinations, their significance cannot be questioned. Evidence indicating a certain degree of mechanical separation by wave washing of light and heavy minerals is seen in the quartz/zircon ratios for these soils which is excessively high for A₂ horizons and low for B₂ horizons, particularly in the anomalous Nappanee.

These petrographic data therefore confirm conclusions earlier deduced from studies of particle sizes and chemical analyses. It is thus possible to state with some degree of assurance that St. Clair represents a mature zonal profile developed in rather uniform parent materials. By the same criterion, further speculation concerning the relative importance of eluviation and illuviation in the genesis of the Nappanee, Conover, and Brookston profiles is known to be fruitless since these studies thus far have revealed no method of reconstructing their original parent material profiles.

CARBONATE-FREE SOLUMS

While surveying soils in Sanilac County, preparatory to securing samples for laboratory comparisons, it became apparent that perhaps a major chemical difference in the four selected series was in the

carbonate content of the horizons of their profiles. Accordingly, a field study of this feature was instituted with the results that are shown in Table 11.

Obvious deductions from these data are that calcite-carbonates³ are encountered at greater depths in Nappanee and Brookston than in the higher and supposedly more weathered St. Clair and Conover profiles. Field observations indicate that these differences are not reflected in either the A₂ or B₂ horizons, the common depths and thicknesses of which are indicated in the table. In the St. Clair and Conover series, free calcite-carbonates are commonly found just below the zone of maximum color intensity in the B horizon. This relationship was not observed in the other two profiles, although a great difficulty with these latter soils was in identifying their B horizons. Observations along freshly dug drainage ditches, however, confirmed evidence obtained from borings to the effect that a zone of free effervescence lies somewhat below the zone of finest texture in the Nappanee and Brookston series.

These differences in the calcite-carbonate profiles are thought to be great enough to justify a field separation of Nappanee from Conover and St. Clair. It is possible, moreover, that the characteristics of this calcite-carbonate profile are related to other more subtle features not

TABLE 11—*Calcite-carbonate profiles of the selected series, as indicated by the number and percent of borings in which treatment with cold HCl produced effervescence*

| Depth (inches) | St. Clair | | Conover | | Nappanee | | Brookston | |
|----------------|-----------|-------|---------|-------|----------|-------|-----------|-------|
| | N | % | N | % | N | % | N | % |
| 0-10..... | — | — | — | — | — | — | — | — |
| 10-14..... | 7 | 2.2 | 14 | 4.9 | — | — | — | — |
| 14-18..... | 33* | 12.4 | 45* | 20.7 | 1 | 0.7 | 1* | 0.5 |
| 18-22..... | 72* | 34.7 | 64* | 43.2 | 2* | 2.2 | —* | — |
| 22-26..... | 102* | 66.2 | 71* | 68.1 | 7* | 7.4 | 2 | 1.5 |
| 26-30..... | 61 | 85.1 | 43 | 83.2 | 13* | 17.1 | 5 | 4.5 |
| 30-34..... | 23 | 92.2 | 22 | 90.9 | 19* | 31.3 | 7 | 8.0 |
| 34-38..... | 12 | 95.9 | 12 | 95.1 | 20 | 46.2 | 21 | 18.6 |
| 38-42..... | 8 | 98.5 | 8 | 97.9 | 43 | 78.3 | 32 | 41.0 |
| over 42..... | 5 | 100.0 | 6 | 100.0 | 28 | 99.2 | 119 | 100.0 |
| Total..... | 323 | | 285 | | 134 | | 198 | |

N is the number of borings in which free effervescence was first encountered at the indicated depth range.

% is the accumulative percent of borings in which effervescence was encountered at the indicated, or shallower depth.

*Indicates the average depth and development of the B horizon.

³So called because cold 1:1 HCl was employed in the field, which produces effervescence with calcitic rather than dolomitic carbonates.

susceptible to measurement by techniques employed in this study, but which are nevertheless indicative of the unique appearance of the Nappanee profile and its taxonomic position in the area in question.

Possible explanations of these differences in carbonate profiles are found in the profile drainage characteristics. Nappanee and Brookston developed in positions analogous to those described by Sherman and Thiel (56) as being susceptible to dolomitization. It is possible that the carbonate content of these two soils has not suffered depletion below the B horizon, but has merely changed to a more dolomitic form which does not effervesce when treated with cold HCl. This explanation is supported by data in the section dealing with the chemical composition of these soils, where it may be noted that even the B horizons contain some carbonates, and that magnesium is present in larger quantities than calcium.

Another explanation of at least a contributing factor is found in the relative susceptibility of the four soils to geologic erosion. Thus the carbonate-free mantle which has developed on the more exposed and higher areas is continually decreasing in thickness, owing to losses of materials from their surfaces. Low-lying soils, however, are not subjected to erosive forces and so, in all probability, do not lose material from the surface; on the contrary, they might be expected to gain material as a result of their low position. Hence the carbonate-free solum in St. Clair and Conover has a tendency to decrease in thickness while that of Brookston increases as a result of these same forces.

PEDOLOGIC INTERPRETATIONS

In the foregoing pages, the author has presented the results of several lines of inquiry into the nature and genesis of the St. Clair, Nappanee, Conover, and Brookston series. The relationship between these four profiles and other Gray-Brown Podzolic soils has also been pointed out. With the evidence now at hand, it becomes possible to integrate these converging approaches with a greater degree of assurance, and to speculate and draw conclusions concerning the processes which have given rise to the mature soil under study. In order to develop the argument, it is first necessary to review certain accepted concepts, together with one or two related fallacies that are sometimes overlooked, so that a basis may be established for the final deductions.

PODZOLIZATION

The generally accepted view of podzolic soil-forming processes, and their effect on soil materials involves the theory of differential solution. In the podzolization process, bases are first removed from materials exposed to soil-forming forces. Then iron, and possibly some alumina, becomes more soluble and is leached downward, leaving the upper solum relatively high in silica. It is thus that the relatively light texture of a podzolized A_2 horizon has been explained. Some material washed out of the surface layers has been thought to move downward through the developing solum until it arrives in a less acid zone where it either flocculates or precipitates to produce an horizon of accumulation. Further it has been assumed that quantities of dispersed clay are carried by the downward movement of percolating water; this infiltrated clay may accumulate in the B horizon either because it flocculates, with the result that particle sizes are increased, or because it reaches a place where the continuous pores are too small to permit farther passage. The A_2 horizon is thus a zone of loss while the B horizon is primarily a zone of gain.

This theory may satisfactorily account for the presence of organic colloids in the ortstein and orterde of sandy ground-water podzols. It may also account for the presence of relatively dark material which coats the exterior of structural units in heavy profiles like the Miami (8). It is difficult, however, to reconcile illuviation with the relatively high interior clay content of structural units in B horizons developed from heavy calcareous tills. Visual evidence shows that while some organic colloids may be translocated in these profiles, they are concentrated on joint planes and as aggregates filling shrinkage cracks. Matrix material, as indicated by color analyses, appears relatively unaffected by translocation. It is, moreover, difficult to conceive how clay might enter the structural units proper since water movements through this heavy material are extremely slow.

From time to time investigators have cast doubt on the theory that large quantities of mineral clay move through the solum as such, but have not presented any convincing refutation. Moreover, the fallacy of expressing analytical results in terms of weight rather than volume has never been widely appreciated, although the customary weight percentages have exaggerated apparent differences resulting from weathering. Horizon comparisons on a weight basis have shown such marked contrasts that it has been difficult to conceive of an explanation

based on other than translocation theories to account for the large differences.

Difficulty has also been encountered in attempts to ascertain the relationship of the solum to underlying unweathered layers, to determine, in fact, whether the solum developed from materials similar to the existing C horizon. This obstacle has been especially great in dealing with the unconsolidated materials of glaciated regions, where lithologic variability is common. Studies dealing with genesis and morphology have therefore been hindered by lack of a method for establishing the uniformity of the original parent material. The technique recently advanced by Marshall fortunately shows promise of offering a solution to this problem.

RESISTANT MINERAL INDICES

Several assumptions are involved in an application of Marshall's resistant mineral method. Important among these are a) that the resistant minerals selected have undergone neither physical nor chemical decomposition; b) that none or insignificantly small quantities of the selected minerals are released as a result of decomposition or disintegration of coarse separates; c) that resistant minerals are present in particles too large to be transported by percolating water; and d) that the resistant minerals are autogenous. Mickelson's work on several Ohio profiles (50) presents a satisfactory rationalization of these difficulties. Although certain necessary assumptions are not entirely satisfied when the method is applied to glacial materials, Mickelson concludes that the errors involved are small enough not to discredit general trends indicated by such studies. An application of the resistant mineral techniques to the series discussed herein therefore appears feasible.

It has already been shown that certain ratios between several resistant minerals justify the conclusion that only one solum, the St. Clair, developed from uniform parent material. Conover, Nappanee, and Brookston all show evidence of having developed from materials characterized by depositional differences prior to their exposure to soil-forming processes. These differences, as indicated by significant variations in certain resistant mineral ratios, are confirmed by dissimilarities in particle size distributions and in total chemical constituents, despite the fact that their color and other easily discernible field characteristics show no visible extremes between the several horizons. Since it can now be concluded with some justification that

the A₂ and B₂ horizons of the St. Clair have developed from material similar in physical, chemical and mineralogical constitution to the underlying C horizon, it is possible to elaborate the genesis of this particular profile.

GENESIS OF THE ST. CLAIR SOLUM

With the data at hand, it is possible to calculate the volume of a representative sample of each horizon associated with one gram of resistant mineral and thereby reconstruct a hypothetical parent profile representing materials as they originally existed when the present land-surface was first exposed to weathering. For this purpose Marshall (45, 46, 51) has proposed the equation $D = \frac{V}{dv}$ where V is the volume of any particular horizon associated with one gram of resistant mineral, v is the volume of parent material containing one gram of the same mineral, and d is the present thickness of the horizon in question. D then represents the original thickness of parent material required to produce the present horizon. Making use of this equation, a weathering factor, based on heavy opaque minerals from very fine sand, has been calculated for the A₂ and B₂ horizons of the St. Clair solum.

Table 12 outlines the reasoning. The results show that both the A₂ and B₂ horizons have suffered a net loss of materials, the former now representing about 60 percent of the volume originally occupied by its parent material. Losses from the B horizon have been much smaller, but it is of interest that these changes are definite losses rather than gains.

TABLE 12—*Calculation of the net changes in parent material to produce equivalent horizon volumes in the St. Clair profile, based on relative quantities of heavy opaque very fine sand*

| Horizon | A ₂ | B ₂ | C |
|--|----------------|----------------|------|
| 1. Percent by weight of organic-free very fine sand in sample (Table 2) . . . | 16.5 | 10.2 | 8.4 |
| 2. Weight in grams of 100 cc. of sample (Table 1) | 137 | 155 | 176 |
| 3. Grams of very fine sand per 100 cc. of sample (Line 1 x Line 2) | 22.6 | 15.7 | 14.7 |
| 4. Percent by weight of heavy fraction in very fine sand (Table 10) | 4.15 | 4.83 | 4.28 |
| 5. Grams of heavy very fine sand per 100 cc. of sample (Line 3 x Line 4) | .936 | .759 | .628 |
| 6. Percent by weight of opaque minerals in heavy very fine sand (Table 10) | 19.3 | 15.9 | 16.2 |
| 7. Grams of heavy opaque very fine sand in 100 cc. of soil (Line 5 x Line 6) | .181 | .120 | .102 |
| 8. Volume of soil containing 1 gram of heavy opaque very fine sand (in cc.) | 552 | 833 | 980 |
| 9. Weathering factor* based on C horizon material as a reference. | 1.77 | 1.18 | 1.00 |

*That is, the number of cc. of parent material required to produce 1 cc. of the present horizon.

TABLE 13—Genesis of the St. Clair profile, net changes being based on the heavy opaque very fine sand index

| | X.CO ₃ | Fine clay | Clay | Silt | Sand | Sum** | VW*** |
|-------------------------------------|-------------------|------------------|--------------------------------|--------------------------------|------|-------|-------|
| A ₂ horizon (index 1.77) | | | | | | | |
| Original weight* | 45.2 | 61.7 | 94.7 | 79.3 | 91.7 | 310.9 | 312 |
| Present weight | 0.0 | 11.1 | 23.4 | 73.0 | 38.6 | 135.0 | 137 |
| Net change (loss) | 45.2 | 50.6 | 71.3 | 6.3 | 53.1 | 174.9 | 175 |
| B horizon (index 1.18) | | | | | | | |
| Original weight* | 30.1 | 41.0 | 63.1 | 52.8 | 61.2 | 207.2 | 208 |
| Present weight | 8.5 | 48.2 | 60.5 | 48.6 | 36.8 | 154.0 | 155 |
| Net change (loss) | 21.6 | -7.2 | 2.6 | 4.2 | 24.4 | 52.2 | 53 |
| C horizon† | 25.5 | 34.7 | 53.5 | 44.7 | 51.8 | 175.5 | 176 |
| | X.CO ₃ | SiO ₂ | Fe ₂ O ₃ | Al ₂ O ₃ | | Sum** | VW*** |
| A ₂ horizon (index 1.77) | | | | | | | |
| Original weight* | 45.2 | 213.0 | 15.2 | 27.8 | | 301.2 | 301 |
| Present weight | 0.0 | 112.9 | 5.6 | 9.0 | | 127.5 | 137 |
| Net change (loss) | 45.2 | 100.1 | 9.6 | 18.8 | | 173.7 | 174 |
| B horizon (index 1.18) | | | | | | | |
| Original weight* | 30.1 | 141.9 | 10.2 | 18.5 | | 200.7 | 208 |
| Present weight | 8.5 | 114.2 | 7.3 | 10.7 | | 140.7 | 155 |
| Net change (loss) | 21.6 | 27.7 | 2.9 | 7.8 | | 60.0 | 53 |
| C horizon† | 25.5 | 120.1 | 8.6 | 15.7 | | 169.9 | 176 |

*Calculated weight of the C horizon material required to produce 100 cc. of the A₂ horizon.

**Summation of the columns to the left.

***Total weights calculated on the basis of the present volume weight of the C horizon.

†The assumed parent material, used in calculating the above values.

Table 13 carries these speculations a step further to show the net changes that may have brought about the evolution of the present St. Clair solum. Here it is seen that both silt and sand particles in the A₂ and B₂ horizons have diminished in size. Sand appears to have disintegrated to a greater extent than silt, indicating that the ultimate grain size of the materials in question apparently falls within the silt range. Clay, and especially fine clay, constitutes the greatest loss from the A₂ zone, but this does not mean that clay minerals are necessarily more susceptible to removal than calcium carbonates, which have entirely disappeared from the upper solum. Losses of clay are much greater from the A₂ than from the B₂ horizon; in fact, the loss from the A₂ is 4 times greater than its present content, from which it is deduced that the clay now in the upper solum is not inherited from the parent material but that it has been formed in place either through synthesis of decomposition products or through disintegration of larger particles.

In the B₂ horizon there has been a net increase in fine clay, a fact that might seem to support the illuviation theory. There has, however, been enough disintegration of larger particles within the B₂ layer materials to account for this entire increase in fine clay. In this con-

nection it is of interest to note that the clay separate as a whole has shown a loss, an indication that even these small particles are undergoing a certain amount of disintegration and chemical attrition.

Another bit of evidence is contained in Table 13 to indicate that illuviation may be responsible for some fine clay in the B₂ horizon. This is seen in the discrepancy between the calculated loss in mass as indicated by volume weight values; and the losses obtained by adding net decreases in silica, iron, and aluminum, a difference amounting to about 7 grams per 100 cc. This is nearly equal to the net increase in fine clay in the B₂ horizon, so that it may be concluded that this illuviated zone has received through translocation within the profile, non-mineral clays to the extent of about 7 grams per 100 cc. of volume. Field observations confirm this conclusion as far as qualitative comparisons are concerned.

The ratio of silica, iron, and alumina in the calculated losses is notable because it closely resembles the ratio in which these same ingredients are found in subsurface drainage waters of this area (see Table 8). Comparison of the values for the A₂ and B₂ horizons shows that initial losses of iron and alumina are relatively large. As the material becomes more and more depleted in iron and alumina, silica losses appear relatively greater, perhaps because the solubility rate of silica does not decrease as rapidly as the solubilities of alumina and iron, and also because silica reserves are much larger than reserves of the latter.

Once a land surface is stabilized by a vegetative cover it is extremely unlikely that colloidal material is lost from the developing solum as a result of either lateral or vertical translocation. Evidence of the inherent stability of soil colloids is readily seen in the clearness of subsurface drainage waters. More probably the fine clay undergoes disintegration (in a manner similar to the larger particles), and then ultimate decomposition, after which the various components leave the soil in an ionic form. This process is naturally more rapid and more extensive in the surface layers; its intensity decreases with depth although chemical weathering still prevails in the B horizon.

The clay of the B horizon, then, has been largely inherited from its parent material. This original clay has probably been modified by other clay formed as a result of larger particles weathering in place and possibly by additions of organic compounds carried down from the surface. It is extremely doubtful that the present B horizon is primarily a zone of illuviation, although illuviation has undoubtedly contributed to its characteristics. More probably, the present physical

nature of the B horizon has been caused by a great loss of basic materials. The absence of these bases has contributed to the plastic characteristics of the inherited clay which has become more easily dispersible and therefore more subject to volume changes caused by alternate wetting and drying. These volume changes have, in turn, promoted the development of a characteristic angular structure, inherited in part from the parent material but modified by an ever-increasing number of joint cracks.

CONCLUSIONS AND SUMMARY

A detailed study of the physical and chemical attributes of calcareous till materials, and of certain profiles that have evolved in these materials within a limited geographical area, has revealed a higher degree of parent material uniformity than has commonly been attributed to glacial drift.

The anomalous Nappanee profile is sufficiently different from other profiles developed in this area to warrant separation as a unique series. On the other hand, the more mature St. Clair profile is so similar to Miami that a separation based only on color, particle size characteristics, and chemical constituents does not appear to be justified. It is recognized, however, that differences in productivity, surface conformation, and other field characteristics may outweigh profile similarities and that the St. Clair series may therefore be justified by attributes that have not been measured or that are not measurable by existing laboratory techniques.

The St. Clair profile has been shown to have evolved from a rather uniform parent material. On the contrary Nappanee, Conover, and Brookston have developed in materials showing definite original dissimilarities between surface and subsurface layers. An hypothesis has been advanced that these differences are depositional in nature and that they may have been caused by wave-action which sorted the surface layers as they emerged from the post-glacial lakes. Wave-washing may have resulted not only in a lateral loss of fine materials from the topmost portions but also in a sorting of the light and heavy minerals, thus producing both a textural and a mineralogical profile before the land surface was fully exposed to soil-forming forces.

In these heavy calcareous tills, soil-forming processes result in the disintegration and decomposition of minerals of all sizes, accompanied by a complete removal of calcium carbonates from the upper solum.

In the so-called zone of accumulation, or illuviated horizon, weathering and leaching are less severe but are still the dominant processes. Thus the heavy clayey characteristics of the B horizon are not primarily caused by the deposition of clay translocated from the overlying layers; more important is the loss of bases, complemented by apparent increases in other less soluble components of the soil mass. Horizon comparisons, expressed in terms of volume rather than weight, indicate that illuviation is probably not so dominant in the formation of the Gray-Brown Podzolic profile as has commonly been supposed.

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APPENDIX I

TECHNIQUE OF PHYSICAL ANALYSIS

It is generally recognized that an investigation into the nature and properties of soils and soil materials depends largely upon the sampling techniques employed. In the final analysis a study is only as good as the samples on which it is based. But perhaps of more importance than mere technique is the personal concept of the investigator, who is inescapably a victim of his own attitudes and bias. A study must therefore be evaluated primarily on the basis of the investigator's experience and objectivity and it is for this reason that no involved sampling procedures are described here. It suffices to say that profile samples were selected not through any random scheme, but rather because each was thought to represent a typical unit in the concept of the modern taxonomist. As a concession to statistical theories, duplicate samples were obtained in order to reveal inherent variations.

VOLUME WEIGHT
AND
POROSITY

Pits were dug to expose what were thought to be representative profiles. Within these pits horizon samples were marked out and separated from adjacent materials by narrow trenches on all sides. Without disturbing the partial monolith so formed, plaster-of-paris was poured around and over it in sufficient quantities to provide an effective support and shield. After hardening, the block and contents were removed, inverted, and transported to the laboratory, thus assuring an undisturbed sample. Two profiles were sampled to permit duplicate laboratory determinations.

In the laboratory, samples of about 200 cc. were selected from each block. From these portions representative structural units were selected for drying and weighing. Oven-dry units were then immersed in melted paraffin, drained and cooled. When cool, their volumes were determined by displacement in water under a vacuum to remove adsorbed air. As a check on volume weight values so determined, the original block was leveled on its open face. Then all soil was removed from the plaster-of-paris mold. The soil was oven-dried and weighed, while the mold was measured as to volume. This procedure yielded a second volume weight value which in every sample agreed well

with the first. An example of the data so obtained is tabulated below:

| Volume weight of the St. Clair A ₂ horizon | | |
|---|----------|----------|
| | Sample 1 | Sample 2 |
| Determined from block subsample | 1.378 | 1.382 |
| Determined from block | 1.366 | 1.357 |
| Average | 1.372 | 1.369 |

Specific gravities were measured by means of a pycnometer, two determinations being made on each sample. Porosities were then calculated using the formula

$$\text{Percent porosity} = 100 - \left(\frac{\text{Volume weight}}{\text{Specific gravity}} \right) \times 100$$

PARTICLE SIZE DISTRIBUTIONS Accumulation curves were obtained on duplicate samples of each horizon in the several profiles by the Bouyoucos hydrometer method (5, 6, 7)¹ modified in minor details (69, 70). Sedimentation temperatures were controlled by a constant temperature bath. Sodium oxalate was used as a dispersant in order to avoid carbonate losses. The resulting accumulation curves were graphically analyzed and supplemented by additional measurements obtained by fractionating coarse sediments with an automatic vertical type sieve. The data were then calculated to an oven-dry basis and organized as Table 2.

Early investigators apparently gave little thought to the fact that calcite and dolomite, although they have disappeared from the upper solum, constitute a rather large proportion of the Gray-Brown Podzolic parent materials. In order to discover the particle size distribution of these carbonate minerals aliquot portions of sands and silts were treated with HCl and boiled until effervescence ceased. The residue was washed several times, then dried and weighed; from these values the amount of carbonate existing as clay was calculated. These results have been integrated into Table 3.

Despite the qualitative nature of these determinations, it is felt that their accuracy is considerably less than errors inherent in sampling. Moreover, the soils in question are characterized by a uniform distribution of various-sized particles. The fact that their summation curves do not exhibit sharp breaks allows the assumption that the hydrometer readings represent points rather than portions of the curve. Although more accurately expressed in the form of settling velocity curves, the data have been calculated to conventional size-frequency distribution classes which are more readily interpreted. It should be noted that

¹Numbers in parentheses refer to the foregoing list of references.

the fine clay class in particular is subject to erroneous interpretation; it is considered sufficiently valid, however, to permit comparisons between the several soils in this study.

APPENDIX II

CHEMICAL COMPARISONS

Samples for the total chemical comparisons were obtained from the materials described in Appendix I. Two hundred grams were set aside for determinations of the bulky constituents, and the sand separates were saved from the mechanical analyses for petrographic examination.

TOTAL CHEMICAL ANALYSES² The official and tentative procedures of the A.O. A.C. (57) were used as a guide. Some departures were made, however, in order to adapt the procedures to the materials and equipment at hand. Determinations were made in duplicate and their averages recorded in Table 4.

Preparation of the Sample—About 30 grams of sample was ground and mixed in an agate mortar. Two 5-gram subsamples from this lot were used to determine hygroscopic moisture so that the ensuing data might be reduced to an oven-dry basis.

Fusion—Approximately one gram of the above sample was weighed on a scoop and then transferred to a 100 cc. nickel crucible. To it was added and mixed 1 gram of sodium peroxide. The mixture was cautiously heated over a Fisher burner until the fusion had quieted. Then about 5 grams of sodium hydroxide were melted into it, the crucible being heated to a barely perceptible redness and slowly rotated. After cooling, the fusion was dissolved with water and transferred to a large porcelain casserole.

Determination of Silica—The contents of the casserole was evaporated to dryness, cooled, and dissolved in absolute methyl alcohol. After several reevaporations in alcohol, the residue was acidified and filtered through Whatman No. 40 paper. The filtrate was returned to the original casserole and again dehydrated with alcohol, and refiltered after acidifying. The filtrate was collected in a beaker and set aside.

²This work was suggested and guided by Dr. G. D. Sherman, formerly a graduate assistant in the Soil Science Section.

Filters bearing the silica from the foregoing procedure were carefully dried and charred in a muffle furnace. Then they were ignited for 30 minutes, cooled, and weighed. After reignition to constant weight the impurities were determined by dissolving the silica with hydrofluoric acid. The residue was ignited to a constant weight, and the difference between the two weights was assumed to be silica.

Impurities from the above were fused with a few crystals of potassium bisulphate, then dissolved in hot water and returned to the main filtrate.

Determination of Aluminum—The aluminum in this filtrate was separated by precipitating all other cations with a solution of sodium-hydroxide-carbonate. The aluminum remained in solution as sodium aluminate. The filtrate was then decanted and acidified with concentrated HCl, using phenol red as an indicator. The solution was then boiled to expel CO_2 and the pH adjusted to 7.5 with concentrated ammonium hydroxide. After digestion on a hot plate, the granular $\text{Al}(\text{OH})_3$ precipitate was separated with a Whatman No. 31 filter. The filtrate was discarded. The precipitate was then dissolved and reprecipitated, washed free of chlorides, and ignited to a constant weight. The hygroscopicity of aluminum oxide was troublesome and the crucible had to be kept covered.

Determination of Iron—The precipitate separated from the sodium aluminate was dissolved with hot HCl and diluted to 200 cc. The iron was then precipitated with ammonium hydroxide, using bromthymol blue as an indicator. The filtrate was set aside for separation of the calcium. The precipitate was taken up with hot sulphuric acid and iron determined by reduction to a ferrous state and titration with standard potassium permanganate. Reduction was accomplished by neutralizing with concentrated ammonia almost to the point of precipitation; the solution was heated to boiling, and then ammonium bisulphite added.

Determination of Calcium—The filtrate from the foregoing separation was heated and the calcium precipitated with ammonium oxalate. Calcium oxalate was separated by a Whatman No. 40 paper. Because of the presence of large quantities of sodium salts a double-precipitation was considered necessary. After igniting to redness in a muffle furnace the residue was dissolved in acetic acid. Reprecipitated with ammonium oxalate, the quantity of calcium present was de-

terminated by titration with potassium permanganate to a faint persistent pink.

Determination of Magnesium—The filtrate from the calcium determination was treated with diammonium phosphate which precipitated as magnesium as $Mg NH_4 PO_4 \cdot 6H_2O$. The latter salt was separated by a Whatman No. 40 filter and ignited at a high heat for 30 minutes, then cooled and weighed. The factor 0.3621 was used to obtain the weight of MgO .

Determination of CO_2 —Carbonate CO_2 was determined by treating a known sample of soil with 1:1 HCl, boiling the mixture to assure the reaction of dolomitic carbonates, and passing the gases through ascarite adsorption bulbs. The increase in weight of the ascarite was reported as CO_2 .

MINERALOGICAL ANALYSES

Petrographic studies were confined to the very fine sand fractions obtained from mechanical analyses. The very fine sand was first separated into light and heavy fractions by means of a heavy liquid, S. tetrabromethane and nitrobenzene, adjusted to a specific gravity of 2.90. These fractions were studied in an exploratory manner to discover what mineral species constituted the bulk of the material; counts were made of the principal species in an attempt to learn essential similarities and dissimilarities.

To effect a separation of the light and heavy fractions, about 2 grams of each sample were placed in small centrifuge tubes containing the heavy liquid. These were centrifuged for three 30-minute periods, each following vigorous stirring of the supernatant mixture. The light minerals were decanted and the heavy fraction was transferred to a small casserole. Both fractions were washed with acetone, dried, and weighed.

The fractions were then spread on gelatinized slides³ to permit the changing of immersion liquids without washing off and losing the particles. Microscopic studies of refractive indices, pleochroism, birefringence, extinction angles, color, and shape were used in identifying the various mineral species. The tables of Larsen and Berman (36) were employed as a standard reference.

³A procedure suggested by Mr. John Young, of the Michigan State College Geology Department, and since described by Marshall and Jefferies (46).

